EUROPEAN COMMISSION

Community research

EURATOM

DOPAS

# DOPAS Work Package 4 Deliverable 4.4: WP4 Integrated Report: Summary of Progress on, and Performance Evaluation of, Design, Construction and Monitoring of Plugs and Seals

Grant Agreement No: 323273

Authors: Matt White and Slimane Doudou (Galson Sciences Limited), Jean-Michel Bosgiraud and Régis Foin (Andra), Oliver Czaikowski (GRS), Dean Gentles (RWM), Pär Grahm (SKB), Erika Holt (VTT), Michael Jobmann (DBE TEC), Petri Koho (Posiva) and Jiri Svoboda (CTU)

Date of preparation: 31 August 2016

Version status: Version 1

| Start date of the project: September 2012 | Duration: 48 months |
|---|---|



| Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Seventh Framework Programme | | |
|---|---|---|
| **Dissemination Level** | | |
| **PU** | Public | X |
| **PP** | Restricted to other programme participants (including the Commission Services) | |
| **RE** | Restricted to a group specified by the partners of the DOPAS project | |
| **CO** | Confidential, only for partners of the DOPAS project | |

| | | | |
|---|---|---|---|
| Scope | Deliverable n°D4.4(WP4) | Version: | 1.0 |
| Type/No. | Report | Total pages | 205 |
| | | Appendixes | 0 |
| Title | WP4 Integrated Report: Summary of Progress on, and Performance Evaluation of, Design, Construction and Monitoring of Plugs and Seals | Articles: | 12 |

| History Chart | | | |
|---|---|---|---|
| Type of revision | Document name | Partner | Date |
| Outline table of contents | WP4 Integrated Report v1d1 | GSL | 19.11.12 |
| Storyboard, building on discussion with ANDRA, NDA and Posiva | WP4 Integrated Report v1d2 | GSL | 01.12.13 |
| Revised storyboard following WP3&WP4 meeting in Prague, December 2014 | WP4 Integrated Report v1d3 | GSL | 19.12.14 |
| Rough draft of the report for partner input | WP4 Integrated Report v1d4 | GSL | 31.12.15 |
| Further draft for final partner input before EE process | WP4 Integrated Report v1d5 | GSL | 18.03.16 |
| Full draft for review using the Expert Elicitation process | WP4 Integrated Report v1d6 | GSL | 05.05.16 |
| Second full draft incorporating response to EE process comments, and distributed for review by partners using review forms. | WP4 Integrated Report v1d7 | GSL | 29.07.16 |
| Final report responding to DOPAS Project partners' comments according to the Review Plan | WP4 Integrated Report v1 | GSL | 31.08.16 |

**REVIEW/OTHER COMMENTS:**

The report is reviewed by DOPAS Consortium members. The report is approved according to RWM practices for report approval. The DOPAS coordinator has reviewed the report and approved for submission.

**APPROVED FOR SUBMISSION:**

Johanna Hansen ***31.8.2016***

## Executive Summary

### *Report Background*

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

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

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

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

Each experiment represents a different stage of development. The Swedish experiment was started prior to the start of the DOPAS Project and was pressurised during the early stages of the Project. The Finnish, Czech and French experiments were designed and constructed during the Project. Initial pressurisation of the Finnish and Czech experiments occurred within the last year of the Project. The French experiment was not pressurised, but dismantling of the experiment was undertaken during the Project. The dismantling activities of the FSS

experiment incorporated additional observations and the collection of additional information related to the properties of the installed components. By collecting further information during dismantling, Andra benefitted from a thorough assessment of the works carried out, at a marginal additional cost. The German tests focused on the early stages of design basis development and on demonstration of the suitability of designs through performance assessment studies and laboratory and mock-up testing, and will feed into a full-scale experiment of prototype shaft seal components to be carried out after the DOPAS Project.

This report is Deliverable D4.4 of the DOPAS Project, and is part of WP4. This work package addresses the performance evaluation of the full-scale experiments in the DOPAS Project. Deliverable D4.4 is the integrated report of WP4. The objectives are to provide an integrated state-of-the-art summary of the outcomes of WP4 of the DOPAS Project, including the main findings of WP2 and WP3, to evaluate the performance of the plugs and seals with respect to their ability to meet the safety functions specified in disposal concepts, and to present the technical and operational issues that have been resolved in the project. This report provides an integrated summary of the progress in design, site selection and characterisation, construction, monitoring and performance, in relation to plugs and seals considered in waste management programmes. The report describes the progress at the time of writing, as defined below.

The report addresses the following questions and topics:

- What has been learnt to date in the DOPAS Project about the ability of plugs and seals designs to meet safety functions specified in disposal concepts?
- What technical and operational issues have been resolved and how?
- What outstanding technical and operational issues remain?
- What is the current status regarding the technical feasibility of installing the reference designs to meet the requirements in the design basis and what modifications are necessary to achieve technical feasibility?

***Main Findings of WP2***

WP2 addressed the design basis of plugs and seals. In the DOPAS Project, a design basis is defined as the set of requirements and conditions taken into account in design. The design basis specifies the required performance of a repository system and its sub-systems, and the conditions under which the required performance has to be provided. The requirements in the design basis form a hierarchy of increasing detail, which is developed in parallel with decisions on the design:

- Stakeholder requirements.
- System requirements.
- Sub-system requirements.
- Design requirements.
- Design specifications.

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

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

During the initial stages of design development, experimental designs are, by necessity, more detailed than the reference designs that they are testing. This is referred to as *concurrent engineering*, i.e. the development of a design at multiple levels of detail at the same time. The results of testing an experimental design may lead to an updated reference design basis.

The application of a hierarchical design basis, concurrent design and iterative development of the design basis were conceptualised in WP2 into a generic DOPAS Design Basis Workflow, which describes the parallel development of designs and their associated design basis. The DOPAS Design Basis Workflow can be applied to all repository sub-systems.

In this report, 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 safety functions (system requirements) and design specifications. The design basis for each experiment includes many tens of design specifications, and it is outside the scope of this report 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 discussed in this report.

There are some differences in the features and processes considered in the 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 design specifications can be recognised. These are:

- Concrete strength.
- pH of concrete leachate.
- Curing temperature of concrete.
- Dry density/swelling pressure of bentonite.

### *Main Findings of WP3*

In WP3, the full-scale experiments were designed and constructed, and a series of *in situ* tests and complementary laboratory investigations have been completed in Germany.

Common approaches to the design and construction of plugs and seals were developed and implemented by the WMOs responsible for different disposal 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.

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 tape, pellet and block systems was undertaken within WP3. Contact grouting was a common feature to all four of the full-scale tests.

The host rock can significantly impact the installation of plugs and seals. Weak rock, the presence of water-bearing fractures and formation of break-outs can be challenging, but approaches were developed and demonstrated in WP3 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 also be parallel installation of other engineered barrier system (EBS) components in a neighbouring tunnel, which may impact on the timing of plug or seal installation, and 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. Experience of plug/seal installation from the DOPAS Project can be used to further develop and plan repository operation sequences.

***Performance Evaluation of the Experimental Work***

*FSS Experiment*

The FSS experiment was a test of the technical feasibility of constructing a drift and intermediate-level waste (ILW) vault seal at full scale. The test box has an internal diameter of 7.6 m and is 35.5-m long. FSS includes a swelling clay core supported by two low-pH concrete containment plugs. Andra tested two types of low-pH for the containment plugs: low-pH self-compacting concrete (SCC) and low-pH shotcrete.

The FSS experiment is focused on the construction 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 (e.g., the REM experiment). Dismantling of the FSS experiment was undertaken between August 2015 and December 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 were 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 backfill in the recesses at the top of the test box. 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.

The FSS experiment has demonstrated that it is feasible to industrially build a horizontal seal system in the Callovo-Oxfordian 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 (underground). The time needed to build a seal is also better estimated at around three months. This is of interest when planning the future Cigéo closure operations.

*EPSP Experiment*

EPSP is a test of materials and technology, extending laboratory experience to the underground environment and to full-scale tests, and building the practical expertise of the SÚRAO personnel and other personnel working on the EPSP project. The experiment consists of two glass-fibre-reinforced low-pH shotcrete plugs separated by a zone containing bentonite pellets and a filter. An injection chamber is located between the inner concrete plug and the back wall of the experiment niche. The 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.

Data on the performance of the EPSP are available for this report up to 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.

The EPSP experiment is the first time that the Czech programme has undertaken a full-scale test of part of the repository EBS, 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 the pressurisation of the system. 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.

*DOMPLU Experiment*

The DOMPLU experiment is a full-scale test of the reference deposition tunnel plug in SKB's repository design. The DOMPLU experiment design consists of an unreinforced low-pH concrete dome with a watertight seal, a filter layer, and a backfill transition zone located upstream of the concrete component. The DOMPLU experiment was constructed inside a tunnel with a horseshoe-shape excavation profile, and 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.

Data on the performance of the DOMPLU experiment are available for this report up to 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 weighed by 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 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 l/min. 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.

*POPLU Experiment*

The POPLU experiment design is based on a wedge-shaped low-pH stainless steel-reinforced concrete structure that is cast in place into a slot that has been notched into the excavation damaged zone. The concrete wedge is cast directly adjacent to a filter layer installed in front of a concrete tunnel back wall. The concrete wedge is contact grouted, and contains grouting tubes and bentonite circular tapes at the rock-concrete interface to ensure water tightness. The steel reinforcement counteracts shrinkage stresses and helps to limit the release of the concrete from the rock. The POPLU experiment was constructed in a tunnel with a horseshoe-shape excavation profile. 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.

During construction and concrete delivery, 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. This report contains monitoring data acquired up to and including 29 February 2016, by which time an initial pressurisation phase had been undertaken in which the experiment had been pressurised to 1.4 MPa. By this time, no displacement, strains or temperature changes in the plug sensors in response to the pressurisation had been detected. Water movement through the POPLU plug was indicated by relative humidity measurements but these data are not yet quality assured, and are therefore not included in this report. There has also not been a significant increase in water pressures measured in the surrounding boreholes, or additional visual leakage detection in the near-field monitoring locations.

Based on the results obtained up to the end of February 2016, the concrete plug itself is not performing satisfactorily when pressurised with free water. During the initial pressurisation of the experiment, leakages were observed, although, following each increase in the pressure, the water leakages decreased indicating that the bentonite tapes were performing as expected. Nonetheless, based on the preliminary pressurisation and monitoring, a decision has been made to re-grout the plug-rock interface to get the detected leakage amounts below the target criterion in the pressurisation plan of 0.1 litres/minute (6 litres/hour) prior to increasing the pressure to the next step. This activity was planned to be undertaken after the freeze date for this report.

The plug monitoring system worked as intended at 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 successfully installed and the majority had sufficient water-protective shielding. The sensors were used to evaluate mechanical load transfer, concrete stresses, location of water during pressurisation and temperature development. Companion samples of concrete were used for evaluation of watertightness (hydraulic conductivity), shrinkage, compressive and tensile strength, and leachate pH.

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

*ELSA, LAVA, LASA and THM-Ton Projects*

The work in ELSA during the DOPAS Project is largely focused on studies that will support the development of a shaft seal design. The aims of the ELSA Project are to develop generic design concepts for shaft seals in salt and clay host rocks that comply with the requirements for a repository for high-level waste (HLW) and to carry out the necessary preparatory work in the shaft seal design project.

Work in the ELSA Project has included a development of a “hard shell – soft core” concept that has been tested in a borehole in the Sondershausen mine in Germany, and development of MgO concrete tested as a plug in a large-diameter borehole also at Sondershausen. In addition, compaction of admixtures of crushed salt and clay intended to be used as a long-term sealing element has been tested *in situ*.

In addition to the above investigations, the laboratory programme of GRS (which is undertaken within the auspices of the LASA, LAVA and THM-Ton projects) address sealing materials planned to be utilised in the shaft seals. This laboratory programme provides supporting information to the ELSA Project. For example, the programme aims at providing experimental data needed for the theoretical analysis of the long-term behaviour of MgO-concrete and cement-based salt concrete in interaction with the host rock and fluids.

***Conclusions***

WP2, WP3 and WP4 of the DOPAS Project have included:

- Collation of the design basis for the 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.
- Detailed design, site selection and characterisation, and construction of the experiments.

- Evaluation of the performance of the full-scale experiments and evaluation of the conclusions from the experiments conducted in the DOPAS Project with respect to the technical feasibility of constructing the reference designs.

The experimental work undertaken in the DOPAS Project has been largely successful. By the time of the freeze date for this report, 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 the results are consistent with the design basis. Additional analysis of the compliance is still ongoing and experiment dismantling and long-term assessment calculations will also be used to assess the compliance of the designs to the safety functions and design specifications.

In the evaluation of the DOPAS experiments undertaken within the scope of the DOPAS Project, there has been a focus on key design specifications, which 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 discussed in this report. On-going evaluation of the experiments undertaken within the DOPAS Project will be carried out by WMOs following the completion of the DOPAS Project, and will consider the full range of issues collated in the design basis.

As a result of the German experimental work, 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 (see further details in DOPAS, 2016c, and Glaubach *et al*. 2016).

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.

The achievements in the DOPAS Project include the following:

- Development of a structured approach to requirements hierarchies that are 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.
- Development and application of techniques for siting repository plugs and seals.
- Application and assessment of techniques for construction of plug/seal slots to high specifications.
- 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 tapes, and use of highly-mobile bitumen to seal the plug/seal-rock interface in anhydrites.
- Demonstration of the application of filters, delimiters and formwork to aid the installation of plugs and seals.
- Adequate monitoring of the performance of plugs and seals using existing monitoring technologies.
- Addressing concerns regarding health and safety by modifying proposed approaches to plug slot excavation.
- Addressing issues with logistics and project management to successfully construct plugs and seals within the timeframe of the Project.

In addition, the work in the 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 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 seal 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.

### List of DOPAS Project Partners

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

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

**List of Acronyms**

| | |
|---|---|
| AECL: | Atomic Energy of Canada Limited |
| ASN: | Autorité de Sûreté Nucléaire (Nuclear Safety Authority in France) |
| BMU: | Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety in Germany) |
| BMWi: | Bundesministerium für Wirtschaft und Energie (Federal Ministry for Economic Affairs and Energy in Germany) |
| Cigéo: | Centre Industriel de Stockage Géologique (Industrial Repository in France) |
| CZ: | Contact zone |
| DOMPLU: | Dome Plug |
| DOPAS: | Full-scale Demonstration of Plugs and Seals |
| EBS: | Engineered barrier system |
| EC: | European Commission |
| EDZ: | Excavation damaged zone |
| EE: | Expert Elicitation |
| ELSA: | Entwicklung von Schachtverschlusskonzepten (development of shaft closure concepts) |
| EPSP: | Experimental Pressure and Sealing Plug |
| FSS: | Full-scale Seal |
| GBT: | Green Break Technology |
| GPR: | Ground penetrating radar |
| HAW: | Higher activity waste |
| HRL: | Hard Rock Laboratory |
| ILW: | Intermediate-level waste |
| ISIBEL: | Review and Evaluation of the Instruments for Assessing Safety of HAW Repositories |
| LASA: | **La**ngzeitsicherer **S**chachtverschluß im S**a**linar (long-term safe shaft closure in salt) |
| LAVA: | **La**ngzeitsicherer Schacht**v**erschluß im S**a**linar (long-term safe shaft closure in salt) |
| LECA®: | Light-weight expanded clay/concrete aggregate |
| LVDT: | Linear variable differential transformer |
| OPC: | Ordinary Portland Concrete |
| PHM: | Physical Hydraulic Model |
| PIM: | Physical Interaction Model |
| POPLU: | Posiva Plug |

| | |
|---|---|
| PVDF: | Polyvinylidene fluoride |
| R&D: | Research and development |
| RSC: | Rock Suitability Classification |
| SCC: | Self-compacting concrete |
| STUK: | The Finnish Nuclear Regulatory Authority |
| TC-Tests: | Triaxial compressions tests |
| TDR: | Time domain reflectometer |
| THM-Ton: | Untersuchung der THM-Prozesse im Nahfeld von Endlagern in Tonformationen (investigation of THM processes in the near field of a repository in clay) |
| URC: | Underground Research Centre |
| URCF: | Underground Rock Characterisation Facility |
| URL: | Underground research laboratory |
| VSG: | Vorläufige Sicherheitsanalyse Gorleben (Preliminary Safety Analysis for Gorleben) |
| WMO: | Waste management organisation |
| WP: | Work package |
| YVL: | Regulatory Guides on nuclear safety (STUK, Finland) |

## Table of Contents

# 1. Introduction

## 1.1 Background

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

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

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

- Clay rocks: the Full-scale Seal (FSS) experiment, being undertaken by Andra in a surface facility at St Dizier, is an experiment of the construction of a drift and intermediate-level waste (ILW) disposal vault seal.
- Crystalline rocks: experiments related to plugs in disposal tunnels, including the Experimental Pressure and Sealing Plug (EPSP) experiment being undertaken by SÚRAO and the Czech Technical University (CTU) at the Josef underground research centre (URC) and underground laboratory in the Czech Republic, the Dome Plug (DOMPLU) experiment being undertaken by SKB and Posiva at the Äspö Hard Rock Laboratory (Äspö HRL) in Sweden, and the Posiva Plug (POPLU) experiment being undertaken by Posiva, SKB, VTT and BTECH at the ONKALO Underground Rock Characterisation Facility (URCF) in Finland, which became a part of the first spent fuel repository in November 2015.
- Salt rocks: small-scale tests related to seals in vertical shafts under the banner of the Entwicklung von Schachtverschlusskonzepten (development of shaft closure concepts – ELSA) experiment, being undertaken by DBE TEC together with the Technical University of Freiburg and associated partners, complemented by laboratory testing performed by GRS and co-funded by the German Federal Ministry for Economic Affairs and Energy (BMWi).

Each experiment represents a different stage of development. The Swedish experiment was started prior to the start of the DOPAS Project and was pressurised during the early stages of the Project. The Finnish, Czech and French experiments were designed and constructed during the Project. Initial pressurisation of the Finnish and Czech experiments occurred within the last year of the Project. The French experiment was not pressurised, but dismantling of the experiment was undertaken during the Project. The German tests focused on the early stages of design basis development and on demonstration of the suitability of designs through performance assessment studies and laboratory testing, and will feed into a full-scale experiment of prototype shaft seal components to be carried out after DOPAS.

This report is Deliverable D4.4 of DOPAS, and is part of WP4. This work package addresses the appraisal of the full-scale experiments in DOPAS. Deliverable D4.4 is the integrated report of WP4.

## 1.2 Objectives

The objectives of this report are to provide an integrated state-of-the-art summary of the outcomes of WP4 of DOPAS, including the main findings of WP2 and WP3, to evaluate the performance of the plugs and seals with respect to their ability to meet the safety functions specified in disposal concepts, and to present the technical and operational issues that have been resolved in the project. This report provides an integrated summary of the progress in design, site selection and characterisation, construction, monitoring and performance, in relation to plugs and seals considered in waste management programmes[1]. The report describes the progress at the time of writing, as defined below. Further description of project results, including consideration of results not available for this report, will be provided in the DOPAS Project in the experiment summary reports (Noiret *et al*., 2016a; Svoboda *et al*., 2016a; Grahm *et al*., 2015; Holt and Koho, 2016; Jantschik and Moog, 2016; Czaikowski and Wieczorek, 2016; and Zhang, 2016) subject to availability of performance data within DOPAS. Results obtained after the DOPAS Project will be most likely reported by each organisation separately at the time of, or after, experiment dismantling.

The report addresses the following questions and topics:

- What has been learnt to date in the DOPAS Project about the ability of plugs and seals designs to meet safety functions specified in disposal concepts?
- What technical and operational issues have been resolved and how?
- What outstanding technical and operational issues remain?
- What is the current status regarding the technical feasibility of installing the reference designs to meet the requirements in the design basis and what modifications are necessary to achieve technical feasibility?

## 1.3 Scope

### *Link to Description of Work Objectives for WP4*

The objectives of WP4 were defined in the DOPAS Project Description of Work, Annex I of DOPAS (2012). The relationship of the original WP4 objectives and the final reporting of the DOPAS Project are as follows:

- **Assess and evaluate the construction methodologies and technologies for plugs and seals (WP3):** The assessment of construction methodologies and technologies for plugs and seals is reported in the WP3 Summary Report (DOPAS, 2016b). High-level summaries of the construction of each experiment are presented in this report as far as

[1] A detailed discussion of design, site selection and characterisation, and construction is included in the DOPAS Project Deliverable D3.30: Design Basis for DOPAS Plugs and Seals (DOPAS, 2016b).

they relate to the ability of plugs and seals designs to meet safety functions specified in disposal concepts.

- **Assess and evaluate the results of the subsequent monitoring phase and the outcome of the dismantling activities to evaluate the predictions against the actual performance:** The monitoring of the experiments will continue after the end of the DOPAS Project and, with the exception of the FSS experiment, the experiments will be dismantled in the future. This report provides an evaluation of the monitoring of the experiments at the current stage of the work (see discussion of freeze dates below). Dismantling activities in the FSS experiment are described in this report and in the FSS experiment summary report (Noiret *et al*., 2016a).
- **Summarise the achievements made in design and the industrial-scale implementation construction, in the light of the specified required performance of plugs and seals as defined in WP2:** The summary is provided in this report.
- **Provide a basis and direct input for performance assessment related activities carried out in WP5:** The work in WP5 focused on evaluation of the performance of the experiments based on existing information and, in the main, did not rely on information provided from WP4. The exception is the REM experiment, for which the design work and results of the FSS experiment were used as a basis for the experimental materials and conditions.
- **Assess remaining uncertainties that may need to be investigated through improvements in design, technologies or materials, or modifications in the construction procedures:** The assessment is provided in this report.

***Link to other DOPAS Deliverables***

This report (D4.4) is part of a series of WP-level summary reports describing the integrated outcomes of the technical work in the DOPAS Project. The reports were produced partly sequentially and partly in parallel, but represent an integrated suite of documents describing the outcomes from the DOPAS Project from the perspective of each WP. As such, there are cross-references between each report, which reflect the position at the end of the project when all of the reports are complete and published. The WP-level summary reports are:

- D2.4, the WP2 Final Report: Design Basis for DOPAS Plugs and Seals (DOPAS, 2016a), describes the design basis for the 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 the full-scale experiment design, i.e. the design of the plug or seal that is being tested in the DOPAS Project.
- D3.30, the WP3 Final Summary Report: Summary of, and Lessons Learned from, Design and Construction of the DOPAS Experiments (DOPAS, 2016b), 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, laboratory work and its upscaling, and the learning provided by the practical experience in constructing the experiments. D3.30 includes detailed photographs of the installation of each full-scale experiment.
- D4.4, the WP4 Integrated Report (this document), summarises what has been learnt with respect to the repository reference designs for plugs and seals. The report also considers alternatives to the reference designs (e.g., the wedge-type plug investigated

by Posiva). It considers what can be concluded from the experiments conducted in the DOPAS Project with respect to the technical feasibility of installing the reference designs, the performance of the reference designs with respect to the safety functions listed in the design basis, and identifies and summarises achievements of WP2, WP3 and WP4 at the time of writing. D4.4 also considers the feedback from the work to the design basis which may include modifications to the design basis.

- D5.10, the WP5 Final Integrated Report (DOPAS, 2016c), describes the conceptualisation of plugs and seals in post-closure safety assessments and the expected behaviour and evolution of plugs and seals over the timeframe of the experiments.

In WP4 and this report, for the FSS, EPSP, DOMPLU and POPLU experiments, we are concerned with the performance of the plugs/seals on a relatively short period, i.e. the performance during the DOPAS Project. This contrasts with consideration of performance of plugs and seals considered in WP5 of DOPAS, which is concerned with modelling of the post-closure evolution of plugs and seals (post-closure performance assessment), consideration of the representation of plugs and seals in total system safety assessment, and also covers a metric-scale experiment (REM) undertaken in support of FSS. Pressurisation of EPSP, DOMPLU and POPLU serves to accelerate the evolution of these experiments, in order for some of the processes monitored to be relevant to longer periods than that over which the experiment is undertaken. Therefore, results of WP4 evaluation can form an input to some of the WP5 work. 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). This is covered in WP4.

- *Full-scale experiment-period performance*, which includes the response of the full-scale experiments to pressurisation during the period of the DOPAS Project. This is covered in WP4.

- *Medium-term performance*, which considers the saturation of the materials used in the experiments (for example in parallel experiments such as REM as the complementary experiment which deals with hydration issues for the FSS bentonite materials) and reference designs, and related modelling. This is only partly covered in WP4 and WP5.

- *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 modelling is covered under WP5.

### *Freeze Dates for Experiment Information in this Report*

D4.4 has been prepared before completion of all related experimental and monitoring work in the DOPAS Project. This report is based on progress up to the following dates:

- FSS: 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 dismantling and rehabilitation of the surface facility was completed in December 2015. Information on all stages of FSS is included in this document.

- EPSP: 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 inner plug was cast in November 2014, the bentonite core was emplaced in June 2015 and the outer plug cast in June 2015. Information available for this report includes preliminary interpretation of the results of monitoring the response to pressurisation of the plug up to 31 March 2016.
- DOMPLU: Excavation work for the DOMPLU experiment was undertaken between February and October 2012. The DOMPLU experiment concrete dome was cast in March 2013 and contact grouting was undertaken in June 2013. Monitoring was undertaken from March 2013. This report includes monitoring data collected in the period up to 30 September 2014.
- POPLU: The design of the POPLU experiment was undertaken between November 2012 and September 2013. Excavation of the experiment tunnel was undertaken in the period September-December 2013, and the excavation of the plug slot was undertaken in the period July 2014-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. Information available up to a freeze date of 29 February 2016 is included in this report.
- ELSA: With regard to the long-term sealing element consisting of crushed rock salt and potentially a clay admixture, laboratory and *in situ* compaction tests had been completed by December 2015. In parallel, a small-scale *in situ* test applying MgO-concrete has been performed (Kudla *et al*., 2015). Small-scale *in situ* tests on the use of bitumen as sealing material were undertaken during 2015 (Glaubach *et al*., 2016). In addition, a laboratory programme undertaken within the auspices of the Langzeitsicherer Schachtverschluß im Salinar (LASA and LAVA) and Untersuchung der THM-Prozesse im Nahfeld von Endlagern in Tonformationen (THM-Ton) Projects addresses sealing materials planned to be utilised in the shaft seals. This laboratory programme provides supporting information to the ELSA Project. Information from all of these activities is included in this report.

Further details on the design and construction schedule and activities for each experiment are provided in D3.30 (DOPAS, 2016b) and in the experiment summary reports (Noiret *et al*., 2016a; Svoboda *et al*., 2016a; Grahm *et al*., 2015; Holt and Koho, 2016; Jantschik and Moog, 2016; Czaikowski and Wieczorek, 2016; and Zhang, 2016). In addition to summaries of the outcomes of WP2 and WP3 in this report (D4.4), the main focus is on monitoring and performance of the plugs and seals, and the learning related to the reference designs. The monitoring and performance 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. Further description of the achievements in the DOPAS Project, based on additional results obtained within the DOPAS Project after the writing of this report, is included in the experiment summary reports (Noiret *et al*., 2016a; Svoboda *et al*., 2016a; Grahm *et al*., 2015; Holt and Koho, 2016; Jantschik and Moog, 2016; Czaikowski and Wieczorek, 2016; and Zhang, 2016).

***Scope of the Experimental Work Undertaken in the DOPAS Project***

As indicated above, the DOPAS Project does not cover the full extent of the work undertaken in each of the full-scale experiments. However, discussion of progress in the technical feasibility of plugs and seals in this report has covered the majority of the activities undertaken in each experiment. For clarification the work on each full-scale experiment that was included in the DOPAS Project was:

- The design, construction and monitoring of the FSS experiment.
- The design, construction and initial monitoring of EPSP.
- 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, although supervision of wire sawing was part of the Project.
- For POPLU: plug design, concrete mix design and performance evaluation, bentonite tape and filter system planning, slot excavation planning and construction, monitoring and pressurisation systems design and implementation, modelling of watertightness and mechanical integrity, pressurisation and performance assessment were part of the DOPAS Project. The plug construction activities of the POPLU experiment were not part of the DOPAS Project.

## 1.4 Terminology

Throughout this report consistent terminology has been applied. This has required, in places, changing the terminology used in a specific programme or within a specific country. The key terms that have been changed in this report for consistency are:

- The term used to describe the combination of materials in a specific concrete is *mix*. In specific cases, this term replaces the use of *formulation* and *recipe*.
- The term used to describe a test of plug/seal components at a reduced scale is *mock-up*. The term *method test* is more frequently applied by Posiva. The tests related to the POPLU experiment would usually be described as method tests by Posiva, in accordance with terminology defined by the Finnish Radiation and Nuclear Safety Authority (STUK) in the Regulatory Guides on nuclear safety (YVL). The use of the term method test by Posiva, communicates that the test is considering *how* a component is installed as well as demonstrating that it can be installed to meet requirements.

## 1.5 Report Structure

This report is presented in the following sections:

- Chapter 2 provides an introduction to plugs and seals, describing, at a high level, the different types of plugs and seals that are expected to be constructed in repositories and the functions they would perform in different types of host rock.
- Chapter 3 describes the approach that has been used within the DOPAS Project to define the design basis for plugs and seals, and to iteratively develop successively more detailed designs in parallel with development and refinement of the design basis. The discussion is captured in an overall generic process for development of the design basis for plugs and seals, referred to as the DOPAS Design Basis Workflow. This section also includes a summary of the approaches used to demonstrate compliance of designs to the design basis. This chapter is based on the WP2 summary report (DOPAS, 2016a). It provides the context for evaluation of the performance of the full-scale experiment in the subsequent chapters.

- Chapters 4-8 provide summaries of the achievements from each experiment and experimental activities (respectively FSS, EPSP, DOMPLU, POPLU and ELSA) with respect to the reference plug or seal design. These summaries are based on the design basis presented in the WP2 summary report (DOPAS, 2016a), the assessment of design work and experiment construction presented in the WP3 summary report (DOPAS, 2016b), the experiment summary reports (Noiret *et al*., 2016a; Svoboda *et al*., 2016a; Grahm *et al*., 2015; Holt and Koho, 2016; Jantschik and Moog, 2016; Czaikowski and Wieczorek, 2016; and Zhang, 2016) and evaluation of the performance of the experiments available at the time of report writing.

  For each experimental work and related activities, and where relevant to the objectives and scope of the work undertaken in the DOPAS Project, the following is discussed:

  - A summary of the reference concept, its design basis, including the safety functions performed by the specific plugs and seals considered in the DOPAS Project, the more detailed requirements addressed by monitoring of the DOPAS Project experiments, and the objectives of the associated work undertaken in the DOPAS Project.
  - A summary of the design and construction of the full-scale tests, or, for the ELSA programme, the *in situ* tests and the complementary laboratory investigations.
  - Where relevant, an evaluation of the siting and excavation of the full-scale experiment with respect to the siting and excavation of the reference concept during repository operation.
  - An evaluation of the operational issues faced during the installation of the full-scale experiment components, including discussion of operational challenges and their mitigation, and how this may affect installation of plugs and seals in a repository.
  - An evaluation of the performance of the full-scale experiment components prior to pressurisation, for example the extent to which the materials used meet the design basis specifications (e.g., concrete materials curing temperature and shrinkage, and bentonite materials density).
  - An evaluation of the performance of the full-scale tests during pressurisation or identified as a result of dismantling. The discussion of FSS includes the understanding gained during the dismantling stage. The discussion of EPSP, DOMPLU and POPLU includes understanding of performance gained through initial pressurisation of the experiment.
  - An evaluation of the monitoring systems used in the DOPAS Project full-scale experiments.
  - An assessment of the results of the experiment with respect to the plug or seal safety functions, design specifications and the objectives of the experiment, including the feedback of the results to the design basis.
  - The overall conclusions from each experiment relating to the plug or seal.

  Further details are provided in the experiment summary reports (Noiret *et al*., 2016a; Svoboda *et al*., 2016a; Grahm *et al*., 2015; Holt and Koho, 2016; Jantschik and Moog, 2016; Czaikowski and Wieczorek, 2016; and Zhang, 2016).

Performance evaluation has focused on safety functions (system requirements) and design specifications. The design basis for each experiment includes many tens of design specifications (see White *et al*., 2014), and it is outside the scope of this report 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 discussed in this report.

- Chapter 9 provides an integrated discussion of the progress in the DOPAS Project on the design, construction and monitoring of plugs and seals, at the time of writing, with respect to the ability of plugs and seals designs to meet the safety functions specified in disposal concepts and with respect to the technical and operational issues that have been resolved in the project.
- Chapter 10 provides a discussion of remaining technical and operational issues and how they may be addressed.
- Chapter 11 provides the conclusions from WP4, as appropriate at this stage of the project.

# 2 Plugs and Seals in Repository Designs

Geological disposal of radioactive waste relies on a series of complementary barriers to provide containment and isolation of the hazardous materials in the waste, thereby meeting regulatory demands. The barriers include the wasteform, waste containers, buffer and backfill materials, plugs and seals, and the host rock, each of which will be effective over different timescales. The depth of disposal, and the characteristics of the host rock and the surrounding geological environment provide isolation from the biosphere and retardation of migrating radionuclides, and reduce the likelihood of inadvertent or unauthorised human intrusion.

As part of the backfilling of a repository, specific parts will have to be plugged and sealed. The purpose of plugs and seals will depend on the disposal concept, the nature of the geological environment and the inventory to be disposed:

- Plugs and seals may be required during operations to isolate and contain emplaced waste packages and surrounding engineered barrier system (EBS) components from the rest of the underground excavations.
- Plugs and seals may be required to limit groundwater flow and/or radionuclide migration following closure of the underground openings.
- Plugs and seals may be required to prevent inadvertent or unauthorised human access.
- Plugs will be required for sealing of investigation boreholes, in particular to intersect and isolate water-conducting fractures and to ensure that the borehole does not act as a radionuclide migration pathway following closure.

A range of different plugs and seals will be employed in a typical repository, as illustrated in Figure 2.1. Safety functions associated with specific plugs and seals are discussed in the experiment-specific chapters of this report (Chapters 4-8).

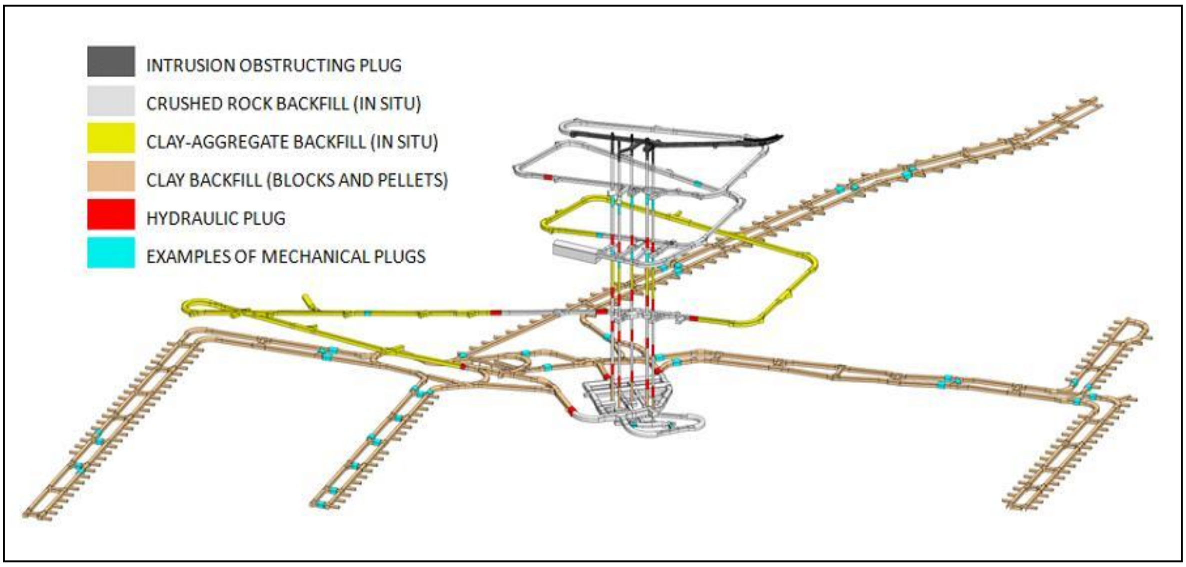



**Figure 2.1:** The sketch for closure backfill and plugs for access tunnels and shafts in the Finnish repository (Posiva, 2012a).

Plugs and seals are designed to work in concert with the other engineered barriers, and the requirements placed on plugs and seals are dependent on the overall repository design. Requirements may be placed on the performance of plugs and seals related to mechanical, hydrogeological and gas migration functions they provide in support of the performance of other engineered structures in the repository. In order to deliver these functions, plugs and seals will need specific thermal, hydraulic, mechanical, chemical and gas migration characteristics. The design basis for plugs and seals is discussed in Chapter 3.

Based on Auld (1996), the following factors need to be taken into account when designing an underground plug:

- The purpose for which the plug is to be constructed.
- The type of excavation in which the plug is to be installed (e.g., a vertical shaft or a horizontal opening), and the impact of the excavation on stress variations around the opening.
- The location of the plug in relation to the prevailing rock and working conditions.
- The head of water to be withstood.
- The strength of, and stresses in, the plug material.
- The method of plug construction.
- The shape of the plug: Auld (1996) identified three types of plug shape:
    - Thin plugs keyed into the rock, including reinforced concrete walls (Figure 2.2a) or unreinforced arches (Figure 2.2b).
    - Tapered and longer plugs with no reinforcement (Figure 2.2c).
    - Parallel plugs (Figure 2.2d, Figure 2.2e and Figure 2.2f).

Plugs in radioactive waste repositories will be required to withstand hydrostatic pressures and mechanical pressures from the swelling of EBS materials, although the illustrations in Figure 2.2 show water pressures only.

The type of host rock plays an important role in defining the design requirements for plugs and seals. High-level impacts can be recognised as summarised below, but the requirements for any particular implementation will depend on the specific nature of the host rock and the disposal concept, and will therefore be more specific and more detailed than described below.

Clay host rocks generally have low hydraulic conductivity, and can be plastic and, sometimes, soft. The plasticity and creep properties of most clay rocks contribute to the self-sealing of any fractures that may develop during the construction and operation of the repository. However, these fractures may become reactivated in the presence of high gas pressures (Zhang, 2014). Underground openings in clay rocks may require lining or mechanical stabilisation during operations; this lining may need to be removed in the plug or seal location to ensure a tight rock-plug/seal interface in order to meet post-closure performance requirements. The repository access ways represent a possible short circuit of the geosphere containment function. Therefore, the key function for plugs and seals in these systems is to close the repository such that groundwater flow into, and out of, the repository is restricted by ensuring that low hydraulic conductivities are reached.

More information on plugs and seals, including description of previous experience with full-scale testing of plugs and seals and the state-of-the-art in plug and seal design at the start of the project is included in the DOPAS Project Design Basis report (White *et al*., 2014) and the Project Summary Report (DOPAS, 2016d).

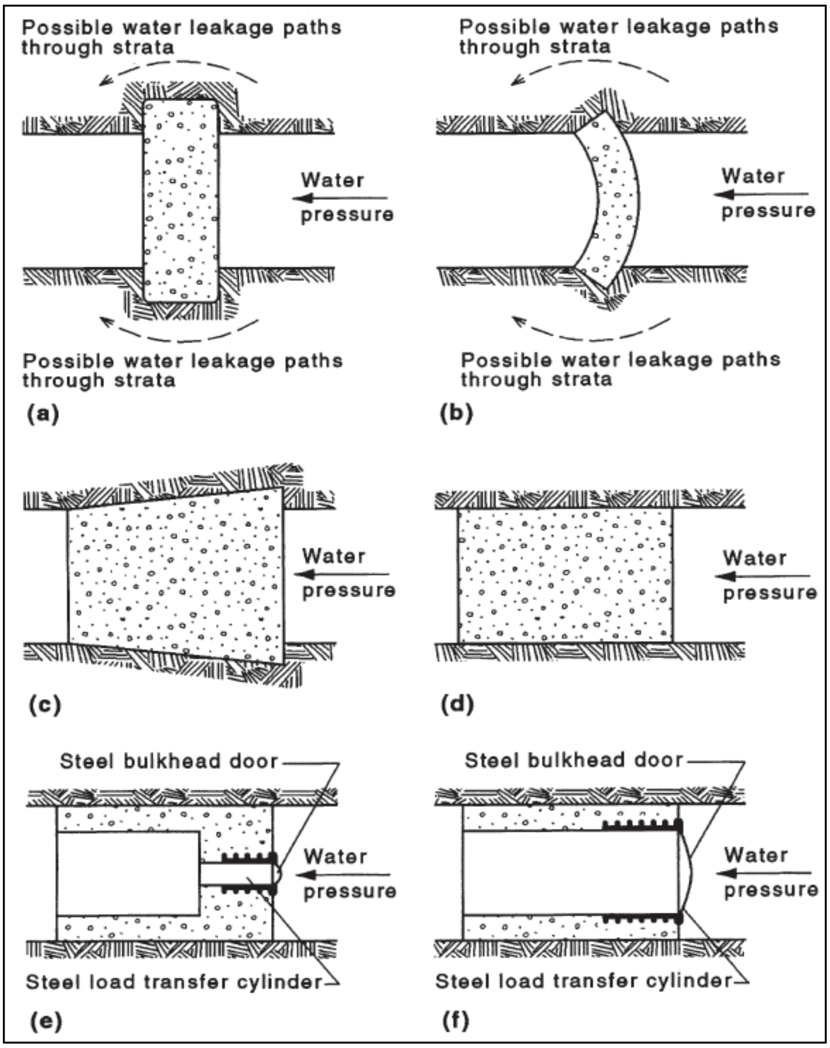



**Figure 2.2:** Basic concrete plug shapes (Auld, 1996). (a) Reinforced concrete wall; (b) Unreinforced concrete arch; (c) Unreinforced concrete tapered plug; (d) Unreinforced concrete parallel plug; (e) Unreinforced concrete cylindrical parallel plug, with human access; (f) Unreinforced concrete cylindrical parallel plug, with roadway access.

Crystalline host rocks can be highly impermeable, but usually consist of fractures that increase their hydraulic conductivity. Crystalline rocks have a high modulus of elasticity (e.g., Young's modulus) and are relatively brittle compared with clay and salt rocks, where creep is an important mechanical property of the rock. Water-conducting fractures may be present and may facilitate groundwater flow. Plugs and seals should provide a low hydraulic conductivity by ensuring a good contact between the plug (often made of concrete) and the rock. In competent crystalline rocks, grouting of the interface between the concrete and the rock, following curing and shrinking of the concrete, is frequently used to achieve this. In addition to contact grouting, bentonite tapes, acting as sealing bands, can help in meeting the hydraulic conductivity requirements or a bentonite watertight seal behind the concrete can be introduced. Successful shrinkage and contact-grouting can also be supported by cooling of the concrete.

In the case of crystalline rock, both the host rock and the excavation damaged zone (EDZ)[2] have potential to provide groundwater flow paths that could short-circuit the plug. Therefore, the plugs must be keyed into the host rock, and the selection and acceptance of each plug location must be based on criteria established in advance. Typically, the criteria aim at avoiding or rejecting volumes of rock where natural fracturing might enable formation of hydraulic connections or groundwater flow paths spanning the entire length of the plug.

Depending on the rate of groundwater flow in a crystalline rock, it may be necessary to introduce a filter layer for drainage to delay the pressurisation of the plug until the concrete has cured and developed sufficient strength to withstand the pressures.

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

Materials used in seals in salt host rocks require chemical compatibility with the host rock for the timescales over which they must function. Materials such as salt concrete and sorel concrete[3] are envisaged. Other materials that may be affected by chemical interactions with the salt can be used, for example bentonite, as long as the period over which alteration of the bentonite occurs is longer than the period over which its swelling properties are required.

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

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

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

# 3 The Design Basis of Plugs and Seals and Compliance of the Designs with the Design Basis

This chapter summarises the work undertaken under WP2 of the DOPAS Project and documented in DOPAS (2016a) concerning the design basis of plugs and seals. It provides the context to the information presented later in the report on the evaluation of the performance of the experiments with respect to the design basis of the DOPAS plugs and seals. Further details on the design basis of plugs and seals can be found in DOPAS (2016a) and references therein. This chapter is structured in four sections:

- Section 3.1 discusses the meaning of "design basis", summarises the way in which design bases are developed by WMOs and presents a hierarchical structure for the design bases for plugs and seals that has been applied within the DOPAS Project. The design basis structure applied in the DOPAS Project may differ from that applied by specific programmes. Therefore, referencing of specific requirements with respect to the proposed hierarchy may differ from the manner in which the requirements are referred to in a specific programme.
- Section 3.2 defines reference and experiment designs.
- Section 3.3 discusses compliance of designs with the design basis.
- Section 3.4 describes a generic process for preparing a design basis for plugs and seals, the DOPAS Design Basis Workflow, which was developed in WP2 of the DOPAS Project.
- Section 3.5 explains the type of requirements that have been considered for experiment performance evaluation as part of this report.

## 3.1 The Design Basis of Plugs and Seals

In the DOPAS Project, a design basis is defined as the set of requirements and conditions taken into account in design. The design basis specifies the required performance of a repository system 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 (i.e., the performance) and what it must be like (i.e., the characteristics). For a plug/seal, this could be, for example, the strength and the hydraulic conductivity of the materials making up the plug/seal. Conditions are the loads and constraints imposed on the design, for example, the underground environment (dimensions, air temperature, humidity, etc.) or controls on the manner in which the design is implemented (e.g., the time available for construction).

The requirements in the design basis form a hierarchy of increasing detail, which is developed in parallel with decisions on the design. At each stage in the design development process, the requirements are used as the basis for more detailed designs. Therefore, although there is a transition from problem specification to solution during design development, requirements are defined at each stage in the process as the basis upon which more detailed designs are developed. For example, development of a disposal system conceptual design requires description of the sub-systems that make up the conceptual design at the same time as developing the statements regarding the functions that these sub-systems must provide. At a more detailed level of design development, designing a specific plug/seal component (e.g., defining a 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 conditions that form part of the design basis are expressed in different ways using different terminologies. However, these processes are largely comparable to each other. Some commonalities that have been identified include:

- Using the experience gained from previous tests and experiments on plugs and seals and/or from underground mining activities.
- Using an iterative process involving the design basis, performance assessment and safety evaluation to fine tune the design basis for the final plug/seal system, paying due consideration to the constructability and durability of these complex structures. This shows that requirements may be subject to change as the design process evolves. The principal safety functions of a plug or seal can be specified and stabilised once the repository concept has been established 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.
- Performing critical design reviews periodically to assess the results, to check the compliance of designs with the design basis, and to 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.

Some WMOs use hierarchies to describe and present the design basis. For example, Posiva and SKB use a five-level requirements hierarchy based on the V-Model (Forsberg and Mooz, 1991) to structure requirements. 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. Furthermore, a structured design basis can link safety functions to design specifications, and, if the design specifications are written appropriately, these can form the basis of construction and quality control procedures.

Building on this context, in the DOPAS Project, the requirements contained in the design basis of plugs and seals are described in terms of the following hierarchy:

1. Stakeholder requirements: Stakeholder requirements are the top-level statements on, and description of, what must be achieved by a waste management programme and elaboration of specific approaches that must be considered in the repository design.
2. System requirements: The requirements on the disposal system, i.e., the safety functions provided by the elements that comprise the disposal system. For plugs and seals, therefore, system requirements are the safety functions provided by plugs/seals.
3. Sub-system requirements: A list of the functions that the components that comprise the plug/seal must provide and the qualities that these components must have.
4. Design requirements: Qualitative statements describing the qualities or performance objectives for plug/seal components.

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

Following the definition of the design basis presented above (the design basis is the "set of requirements and conditions taken into account in design"), the argument that the design basis is developed in parallel with decisions on the design, and that at each stage in the design development process requirements are used as the basis for more detailed designs, it is appropriate for all of the statements contained at all levels of the hierarchy to be referred to as "requirements", with clarification added by use of the more specific term. This approach has been adopted throughout this report.

However, a strict hierarchical structure was not imposed on the detailed design bases developed in the project (see White *et al*., 2014) because, at the time of development of the design bases, a common methodology, known to be applicable to all disposal programmes addressed in the DOPAS Project, was not available.

## 3.2 Reference and Experiment Designs

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

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

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

During the initial stages of design development, experimental designs are, by necessity, more detailed than the reference designs that they are testing. For example, reference designs may only be developed to the conceptual level. The testing of the conceptual design at the detailed level in a full-scale experiment allows requirements to be clarified and to establish feasibility for one or other design solutions. Testing of this sort is sometimes referred to as *concurrent engineering*, i.e. the development of a design at multiple levels of detail at the same time (NASA, 1995; Carter and Baxter, 1992). The results of testing an experimental design may lead to an updated reference design basis and reference design.

## 3.3 Compliance

Compliance of designs with the design basis may be considered as comprising both verification and validation (NASA, 1995). Verification consists of proof of compliance with design specifications, and may be determined by, for example, a test, analysis, demonstration or inspection (e.g. measurement of slump flow to determine rheological properties of a concrete). Validation consists of proof that the system accomplishes (or can accomplish) its purpose. It is usually much more difficult (and much more important) to validate a system than to verify it. Validation can be accomplished only at the system level, while verification must be accomplished throughout the entire system hierarchy (NASA, 1995). Using this concept of validation, the term is most readily applied to compliance of plug/seal designs with the safety functions for these sub-systems in the overall disposal concept. Verification and validation of designs should not be confused with verification and validation of computer models of physical and chemical processes (see, for example, Oreskes *et al.*, 1994; and Pescatore,1995).

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 and predict performance (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.
- 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).

Compliance of designs with the design basis is discussed further throughout this report with respect to the evaluation of the performance of the DOPAS Project experiments with respect to the reference design basis.

## 3.4 The DOPAS Design Basis Workflow

Work on the design basis in the DOPAS Project has allowed consideration 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 3.1). The terms used in the workflow are defined in the glossary of DOPAS (2016a) and are consistent with the IAEA glossary (IAEA, 2007). The workflow is structured to be consistent with a hierarchy of increasingly detailed designs (IAEA, 2001), as follows:

- Conceptual Design: Conceptual designs describe the general layout of a repository structure, including the different repository components and how they are arranged, and the type of material used for each component (e.g., concrete, bentonite, gravel). In a conceptual design, the environmental conditions (including rock characteristics) are presented in generic terms, for example by describing the nature of the processes occurring rather than quantifying the processes. The performance of the components and the overall structure are 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.

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

At the basic design stage, 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 experiment design specifications, which are used to design the experiment and as the basis for performance evaluation. These design specifications represent working assumptions for reference design specifications, which might be adopted as reference design specifications following evaluation of experiment 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).

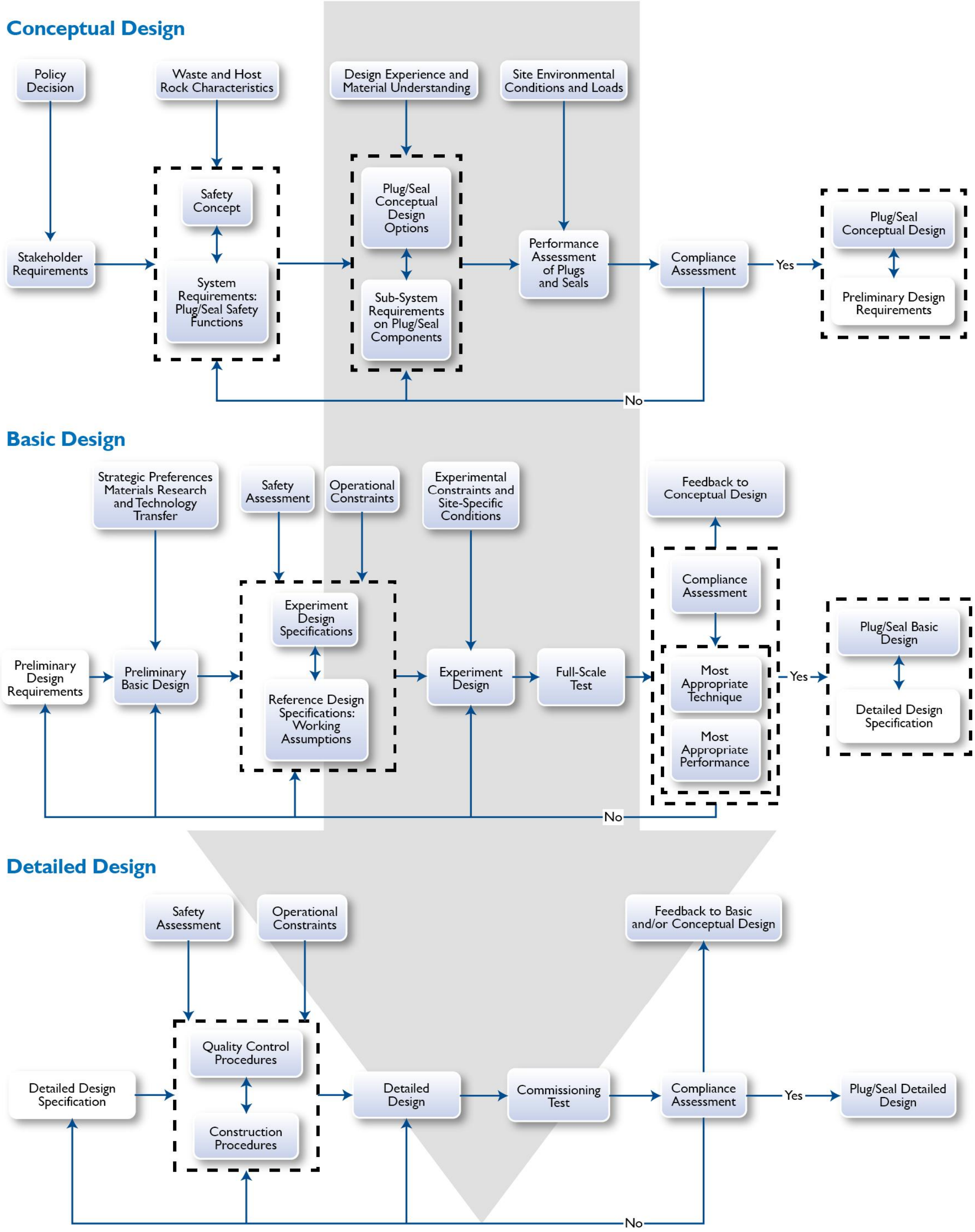



**Figure 3.1:** The DOPAS Design Basis Workflow, which illustrates the iterative development of the design basis, undertaken in parallel with the development of conceptual, basic and detailed designs. Dashed boxes are used to show activities undertaken in parallel. Terminology used in the Workflow is defined in DOPAS (2016a), which includes a glossary of the terms in the Workflow.

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.

At the detailed design stage, 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 may be 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).

The DOPAS Design Basis Workflow is based on the design basis work undertaken for plugs and seals within the DOPAS Project. The Workflow is described in more detail in the WP2 Summary Report (DOPAS, 2016a), including definition of the terms and provision of a glossary. However, the Workflow is generic in nature, and could be applied to other repository design activities. The general applicability of the DOPAS Design Basis Workflow was considered as part of the wider DOPAS Project dissemination activities (WP7) (e.g., the Workflow was presented at the Lucoex 2015 Conference and at the DOPAS 2016 Seminar) and is discussed in the Project Summary Report (DOPAS, 2016d).

### 3.5 Consideration of the Design Basis in Experiment Performance Evaluation

In Chapters 4, 5, 6 and 7, the performance of the full-scale experiments conducted in the DOPAS Project is presented and compared to the design basis developed in WP2. In order to undertake this evaluation, a sub-set of the design basis requirements has been considered:

- The safety functions (system requirements) for each plug and seal are evaluated.
- “Key” design specifications that were addressed through design work (materials development and testing, including associated numerical modelling), experiment construction (including associated quality control) and experiment pressurisation are evaluated. The list of key design specifications has been selected based on expert judgement of the DOPAS experiment leaders and project partners to represent some of the principal design specifications that need to be considered in plug and seal performance, but does not include all design specifications. Further analysis of experiment performance by each WMO will consider the full range of design specifications collated in the design basis as reported in the DOPAS Project Design Basis Report (White *et al.*, 2014). Comprehensive analysis of every requirement in each experiment design basis is outside the scope of the DOPAS Project.

# 4 Andra's Drift and ILW Vault Seal

This chapter discusses the achievements in the DOPAS Project, in particular the design, construction and dismantling of the FSS experiment, with respect to Andra's reference drift and ILW vault seal:

- In Section 4.1, the design basis for the drift and ILW vault seal is described, focusing on the safety functions assigned to the seal, a summary of the reference design, and presentation of the key design specifications contained within the design basis and which are directly tested through measurement and monitoring of the FSS experiment. More information on the design basis can be found in White *et al*. (2014).
- In Section 4.2, the FSS experiment is described, including the objectives of the experiment, and a summary of the design work, construction of the test box and installation of the FSS components. More details on the construction of the FSS experiment are in DOPAS (2016b).
- Section 4.3 discusses the learning from the FSS experiment with respect to the operational issues that will be faced during installation of Andra's reference drift and ILW vault seal.
- In Section 4.4, the performance of the FSS components is evaluated, and conclusions drawn regarding the suitability of the materials and the emplacement methods used to install the materials for application in the repository.
- Section 4.5 evaluates the results achieved from the dismantling of FSS.
- Section 4.6 evaluates the performance of the measurement system used in the FSS experiment and its applicability in repository monitoring.
- Section 4.7 presents an evaluation of the compliance of the FSS experiment with the design basis, the feedback of the results to the design basis and discusses the learning outcomes from the work.
- Section 4.8 presents the overall conclusions from the FSS experiment relating to Andra's reference drift and ILW vault seal.

The information presented in this chapter focuses on a summary of the performance of the experiment. In addition to the further information on the design basis and construction of the FSS experiment provided in other reports and references therein as indicated above, further details on the FSS experiment are provided in the FSS experiment summary report (Noiret *et al*., 2016a).

As discussed below, the FSS experiment does not address the long-term behaviour of Andra's reference drift and ILW vault seal. Long-term behaviour is addressed in complementary experiments, including the REM experiment, which is described in the WP5 summary report (DOPAS, 2016c) and references therein.

## 4.1 Design Basis for Andra's Drift and ILW Vault Seal

### 4.1.1 Drift and ILW Vault Seal Safety Functions

In France, high-level waste (HLW) and ILW will be disposed of in a repository referred to as the "Centre Industriel de Stockage Géologique" (also known as Cigéo) (Andra, 2013). 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 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 in the following qualitative sense:

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

#### 4.1.2 Drift and ILW Vault Seal Design

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 consists of a swelling clay core and two concrete containment walls (Figure 4.1). The swelling clay core provides the required long-term performance of the seal, whereas the containment walls are included to mechanically contain the clay 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 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.

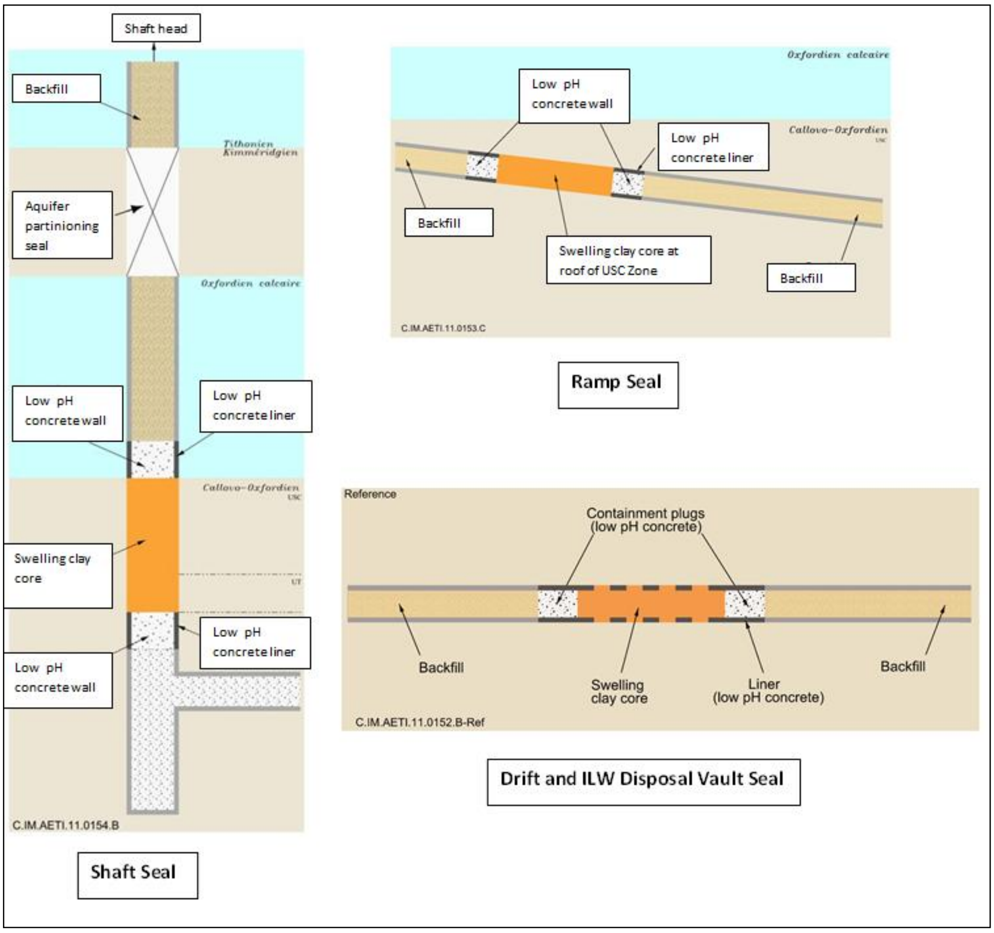



**Figure 4.1**: Schematic illustration of the conceptual designs for shaft, ramp, and drift and ILW disposal vault seals for the Cigéo reference disposal concept. From Wendling *et al*. (2015).

#### 4.1.3 Key Design Specifications in the FSS Design Basis

The key design specifications contained within the design basis and which are directly tested through measurement and monitoring the FSS experiment or during materials development are presented in Table 4.1. More information on the design basis can be found in White *et al.* (2014). The full design basis contains a much greater number of requirements; only the most significant design specifications have been listed here and are considered in this summary report (see Section 3.5 for context and justification for the selection of "key" design specifications). Evaluation of the performance of the FSS experiment compared to the design basis is an on-going activity within Andra.

**Table 4.1:** Key design specifications tested through measurement of the results of the FSS experiment or during materials development as part of the experiment.

| ID | Design Specification | Justification | Compliance Approach |
|---|---|---|---|
| FSSDS01 | 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 mixes were tested in the laboratory (B50 CEM III/A; B50 CEM I; and B40 CEM III/A). |
| FSSDS02 | The maximum curing temperature of the concrete and shotcrete of containment walls shall not exceed 50ºC. | Ettringite can form in concrete with curing temperatures above 70°C and lead to expansion and cracking, and a consequent loss of strength in the concrete (e.g. Kelham, 1997). 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. ~20 ºC). | Measurement of peak curing temperature in the SCC and shotcrete containment walls. |
| FSSDS03 | The strain as a result of shrinkage of the concrete shall be less than 350 µm/m at 90 days. | This design specification is linked to a design requirement which states "*The heat of hydration shall not cause the temperature to generate heterogeneities in the mechanical behaviour of concrete or shotcrete, in particular causing localised cracking.*"<br><br>The concrete walls need to confine the swelling clay core and withstand a swelling pressure of up to 7 MPa. Temperature gradients result in cracking that would reduce the strength of the concrete walls and create an interface resulting in larger than expected displacements of the concrete walls.<br><br>A temperature gradient that would result in cracking has not yet been defined in Andra's programme. Therefore, the requirement has been defined in terms of strain. A strain of 350 µm/m has been specified by reference to more traditional values (500 µm/m) that are commonly found in civil engineering. | Monitoring of strain (shrinkage) in the concrete walls. |
| FSSDS04 | Cracking of the concrete shall be minimised to be as small as possible. | Cracking would reduce the strength of the concrete walls. Cracking could also lead to flow through the concrete walls, which may lead to bentonite erosion and, consequently, a reduction in density of the clay. | Observations during dismantling to confirm no through-going cracks have formed in the concrete monolith. |

| ID | Design Specification | Justification | Compliance Approach |
|---|---|---|---|
| FSSDS05 | The low-pH SCC shall have a characteristic compressive strength of at least 30 MPa at 28 days and 40 MPa at 90 days. | The values are for standard concrete strength, and they are consistent with parameters used in Andra's models. | During the materials development phase, the low-pH SCC was tested in the laboratory. In addition, tests were undertaken of the low-pH SCC containment wall constructed at full-scale. These tests included measurement of surface hardness and sonic velocity in order to demonstrate the quality of the emplaced concrete consistent with existing standards. |
| FSSDS06 | The low-pH shotcrete shall have a characteristic compressive strength of at least 25 MPa at 28 days and 35 MPa at 90 days. | The values are for standard concrete strength, and they are consistent with parameters used in Andra's models. | During the materials development phase, the low-pH shotcrete was tested in the laboratory. In addition, tests were undertaken of the low-pH shotcrete containment wall constructed at full-scale. These tests included measurement of surface hardness and sonic velocity in order to demonstrate the quality of the emplaced concrete consistent with existing standards. |

| ID | Design Specification | Justification | Compliance Approach |
|---|---|---|---|
| FSSDS07 | 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 1 x 10$^{-11}$ m/s throughout the core.*"<br><br>A long-term effective mechanical stress (i.e. following saturation) of 7 MPa is required to counter-balance the host rock natural mechanical stress (less than natural stress can result in reactivation of EDZ, higher than natural stress results in more fractures). The effective mechanical stress is a result of an *in situ* stress of 12 MPa balanced by 5 MPa pore pressure (hydraulic head), resulting in 7 MPa. During material testing, the dry density value of 1,620 kg/m$^3$, corresponding to a swelling pressure of 7 MPa after hydration, was specified to ensure that the required swelling pressure could be achieved.<br><br>Performance assessment studies conducted prior to the DOPAS Project showed that the seal performance can meet the prescribed safety functions (see Section 4.1.1) with a hydraulic conductivity of 1 x 10$^{-9}$ m/s. However, 1 x 10$^{-11}$ m/s was specified for the FSS experiment because it was considered by Andra to be an achievable value. The density required to achieve a hydraulic conductivity of 1 x 10$^{-11}$ 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.<br><br>Further details on the design work that led to the dry density specification are provided in DOPAS (2016b). | Compliance with the density requirement was determined through mass balance of the bentonite materials used in FSS, time domain reflectometer (TDR) measurements and gamma-gamma logging. |

## 4.2 Summary of FSS Experiment

### 4.2.1 Objectives of FSS

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" at a surface facility (Bosgiraud and Foin, 2013). 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 (the design of the test box is summarised in DOPAS, 2016b; and is described in detail in Bosgiraud and Foin, 2013). The conceptual design of the FSS experiment is illustrated in Figure 4.2.

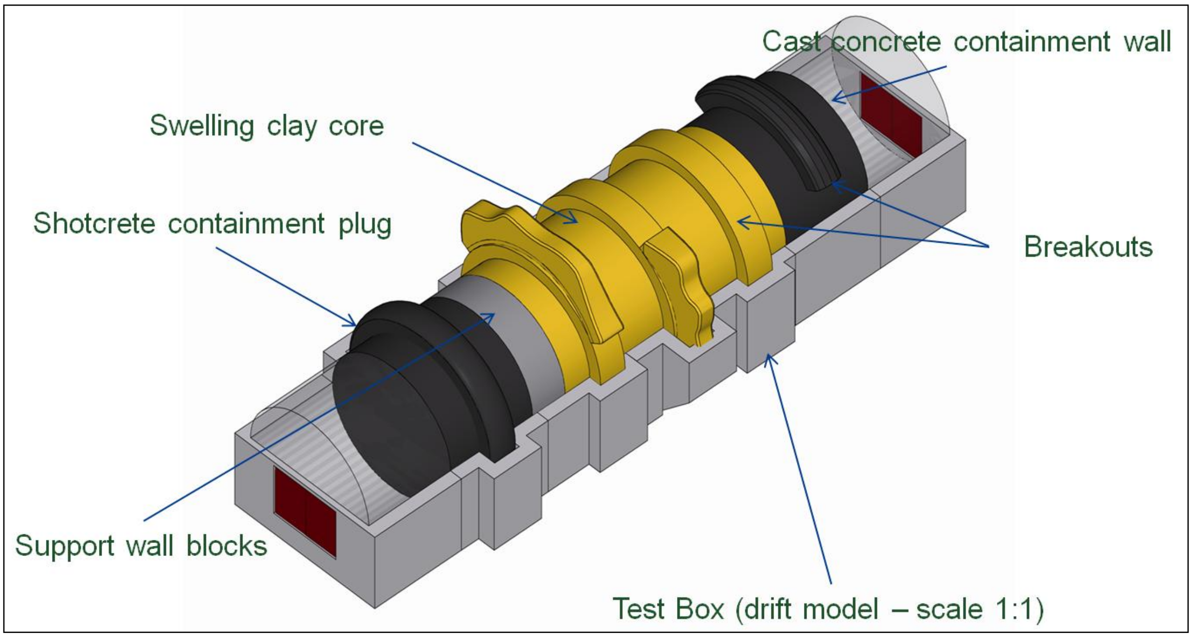



**Figure 4.2**: Schematic illustration of the FSS experiment design. From Bosgiraud and Foin, (2013).

The main difference between the reference design and FSS design for the Andra drift and ILW vault seal is the length of the clay core (13.5 m in FSS). The clay core of the real seal underground will be longer than that considered in FSS (it will be at least 20 m in Cigéo). 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 will not be 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 modelled and undertaken in a surface laboratory with the same pellets/powder mixture as used in FSS.

Although not pressurised, the FSS experiment has been dismantled within the period of the DOPAS Project (see Section 4.5 for a discussion of the results). The dismantling activities of the FSS experiment incorporated additional observations and the collection of additional information related to the properties of the installed components. By collecting further information during dismantling, Andra benefitted from a thorough assessment of the works carried out, at a marginal additional cost.

#### 4.2.2 Summary of FSS Design and Construction

The design and construction of FSS included the following activities:

- Materials development and testing to select the concrete mix for the low-pH SCC containment wall, the concrete mix for the low-pH shotcrete containment wall, and the bentonite materials for the low-pH swelling clay core.
- Siting and construction of the FSS test box.
- Installation of the components.

A summary of these activities is provided below. Further details are provided in the WP3 summary report (DOPAS, 2016b) and the FSS experiment summary report (Noiret *et al*., 2016a) and references therein.

***Materials Development and Testing: Including Compliance with FSSDS01, FSSDS05 and FSSDS06***

Selection of the low-pH SCC mix was based on a series of laboratory and metric-scale tests in which eight binder options were down-selected based on measurement of properties and performance in the metric-scale tests (DOPAS, 2016b; Noiret *et al*., 2016a). Properties measured included pore solution pH, compressive strength, curing temperature and porosity. Observations during metric-scale tests included distribution of aggregates, aggregate/paste separation and bleed water. The final selection of the preferred mix was based on a global analysis of pH, shrinkage, manufacturer location, workability, presence of organic matter and cost. The mix selected was B50 CEM III/A 52.5 Rombas, which is a mix containing 50% cement and 50% silica fume.

Three candidate mixes for the low-pH shotcrete were subjected to test spraying of metric test panels (DOPAS, 2016b; Noiret *et al*., 2016a). The panels were tested for compressive strength, pH, porosity, workability and shrinkage, and the observed rebound was recorded. The selection of the preferred shotcrete mix was also based on a global analysis, which considered the same parameters as for the global analysis of the low-pH SCC, plus the odour of the mixture resulting from sulphur present in the slag materials and the compressive strength. The mix selected was B50 CEM I 52.5 Le Teil, which is a mix containing 20% cement, 32.5% silica fume and 47.5% slag.

For the swelling clay core, Andra selected a pellet-based system instead of pre-compacted bentonite blocks because this solution is considered by Andra to be a more efficient industrial method of implementation at a scale such as that encountered in Cigéo. Andra specified the use of a pure sodium bentonite, without any other constraints, for the swelling clay core. The contractor chose WH2 bentonite (a product similar to MX80) from Wyoming. The initial requirements on the swelling clay materials focused on the swelling pressure and hydraulic conductivity; these are 7 MPa and 1 x $10^{-11}$ m/s, respectively (see Table 4.1). During material testing, the dry density value of 1,620 kg/m$^3$, corresponding to a swelling pressure of 7 MPa after hydration, was initially specified to ensure that the required swelling pressure could be achieved. The density required to achieve a hydraulic conductivity of 1 x $10^{-11}$ 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 (DOPAS, 2016b; Noiret *et al*., 2016a).

The bentonite was emplaced as an admixture of 32-mm diameter pellets and powder to meet the density requirements (DOPAS, 2016b; Noiret *et al.*, 2016a). Laboratory testing demonstrated that this was best achieved through use of crushed pellets rather than standard WH2 powder (the crushed pellets are referred to as "powder"). Mock-up testing used as part of the emplacement machine design process further demonstrated that the admixture was most efficiently emplaced when using screw augers with the auger supplying the pellets positioned beneath the auger supplying the powder. In parallel with the mock-up tests, further investigation into the required swelling pressure concluded that a pressure of 5 MPa would be sufficient to meet the safety functions of the seal. In parallel to the FSS experiment implementation, a proper dimensioning of the containment walls was carried out by Andra, showing a significant impact of the swelling pressure on the containment wall size for the repository seal. Subsequently, the 5 MPa value was also chosen as a reasonable compromise between the containment wall geometry and long-term performance. 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$^3$.

***Siting and Construction of FSS***

FSS was constructed in a surface warehouse as it provided the most suitable solution with respect to logistical limitations of conducting the experiment underground at the Bure URL, it was most favourable in terms of other activities already planned at Bure, and it was favoured in terms of experimental cost, schedule and requirements on dismantling.

The FSS test box (or drift model) design concept was specified by Andra to contain the FSS experiment. The test box was constructed of standard Ordinary Portland Concrete (OPC) using standard construction techniques and was keyed into the facility floor for structural stability. The box was fitted out with a local "mine-like" exhaust ventilation system, with a closing door in the front of the box, in order to control the ambient temperature (18°C < q < 30°C) and humidity (50% < HR < 75%) inside the box, consistent with a requirement on the experiment specification to simulate actual *in-situ* conditions. It was also equipped with polycarbonate observation windows at its periphery to visually evaluate the backfill.

Installation of FSS started with the construction of the first concrete containment wall inside the test box (low-pH SCC) followed by bentonite clay core emplacement in parallel with a support wall made of low-pH concrete bricks. The last installed component of FSS was the second containment wall made of low-pH shotcrete. The installation of the measurement system was undertaken in parallel with installation of the other components.

Further details on the design and construction of FSS are provided in the WP3 Summary Report (DOPAS, 2016b) and the FSS experiment summary report (Noiret *et al.*, 2016a) and the references contained therein.

## 4.3 Learning Related to Operational Issues

The lessons learned from construction of FSS and the implications for installing seals in Cigéo are summarised as follows (further details are provided in DOPAS, 2016b and Noiret *et al.*, 2016a):

- For the low-pH SCC, it was found that the temperature at the experiment site impacts on concrete, therefore, this will need to be appropriately managed underground. It was decided not to pour concrete when the ambient temperature was greater than 26°C (see D3.30 – DOPAS (2016b) for background, Section 2.5.1). The ambient temperature underground in the Cigéo repository at the time of containment wall emplacement will similarly impact the curing temperature, and hence the performance of the concrete. Although this situation is not expected to arise in Cigéo, mitigation measures, such as the use of cooled water for the concrete mix or the positioning of cooling pipes inside the containment wall, could be implemented if this situation would arise.

- During clay core emplacement, one of the main challenges was dealing with the dust generated by handling of bentonite in the warehouse. This was the main health hazard issue in FSS. Bentonite materials transfer and handling systems will have to be optimised to minimise the dust generated (e.g., by using a conveyor system and dust covers), while specific (additional) ventilation will have to be installed. Other ventilation/dust suppression methods could also be incorporated alongside the filling processes (e.g., water mist). In practice, the main operational safety issue is not linked to the seal construction *per se*, but to the preparatory work, when partial dismantling of the drift liner will have to be carried out and followed by purging of the host formation (to get rid of flakes at the contact with the formation wall).

- The use of shotcrete in a mine-like environment can be very useful in building maintaining structures (drift walls in particular: in this application the maximum layer of shotcrete does not exceed a thickness of some 15 to 20 cm). In the case of low-pH concrete containment walls, where the cumulative thickness of layers is several metres, the heterogeneity of low-pH shotcrete and the cleaning/purging of rebounds is a challenging issue. In addition, the mechanical characteristics of shotcrete are significantly heterogeneous by comparison with those of a low-pH SCC. It is, therefore, recommended to limit the use of low-pH shotcrete to less significant components when building a containment wall (e.g., surfacing the concrete bricks forming the support wall) and during the construction of the vault/drift wall (e.g., shotcrete might be used for building the initial temporary drift wall support while SCC is for the final drift liner). More discussion of this issue is covered in DOPAS (2016b).

## 4.4 Performance of FSS Components based on Measurement and Monitoring during Installation

In this section the performance at the time of installation of the FSS experiment with respect to the design specifications listed in Table 4.1 is evaluated:

- Section 4.4.1 discusses the performance of the SCC and shotcrete containment walls with respect to the curing temperature (FSSDS02) and strain (FSSDS03) design specifications.
- Section 4.4.2 discusses the performance of the bentonite swelling clay core with respect to the bentonite density design specification (FSSDS07).

The systems used to measure and monitor the installation of FSS are described in DOPAS (2016b), and are illustrated in Figure 4.3 and Figure 4.4.

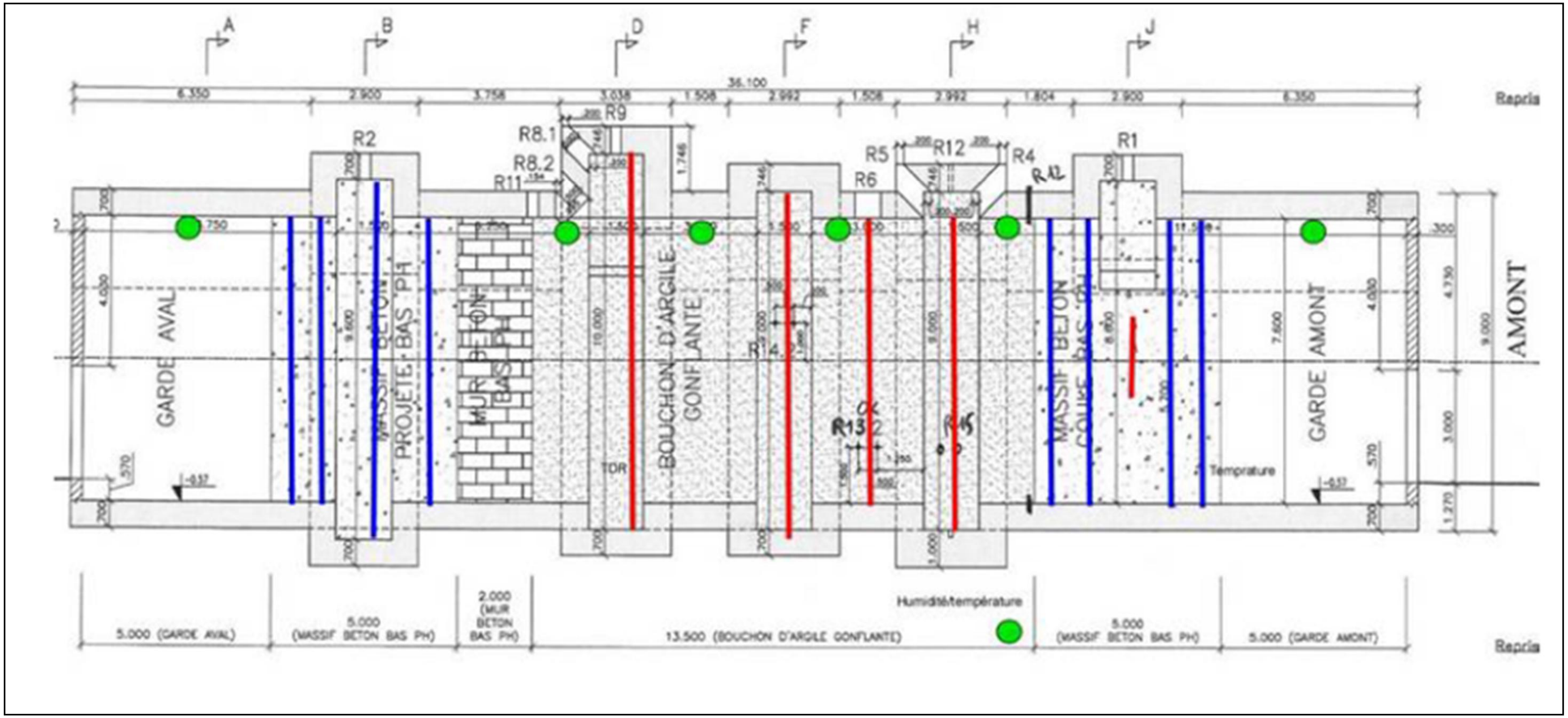



**Figure 4.3**: Location of the different sensors in FSS (blue: strain and temperature sensors in the low-pH concrete containment walls; green: relative humidity and temperature sensors; red: TDR sensors located in the swelling clay core).

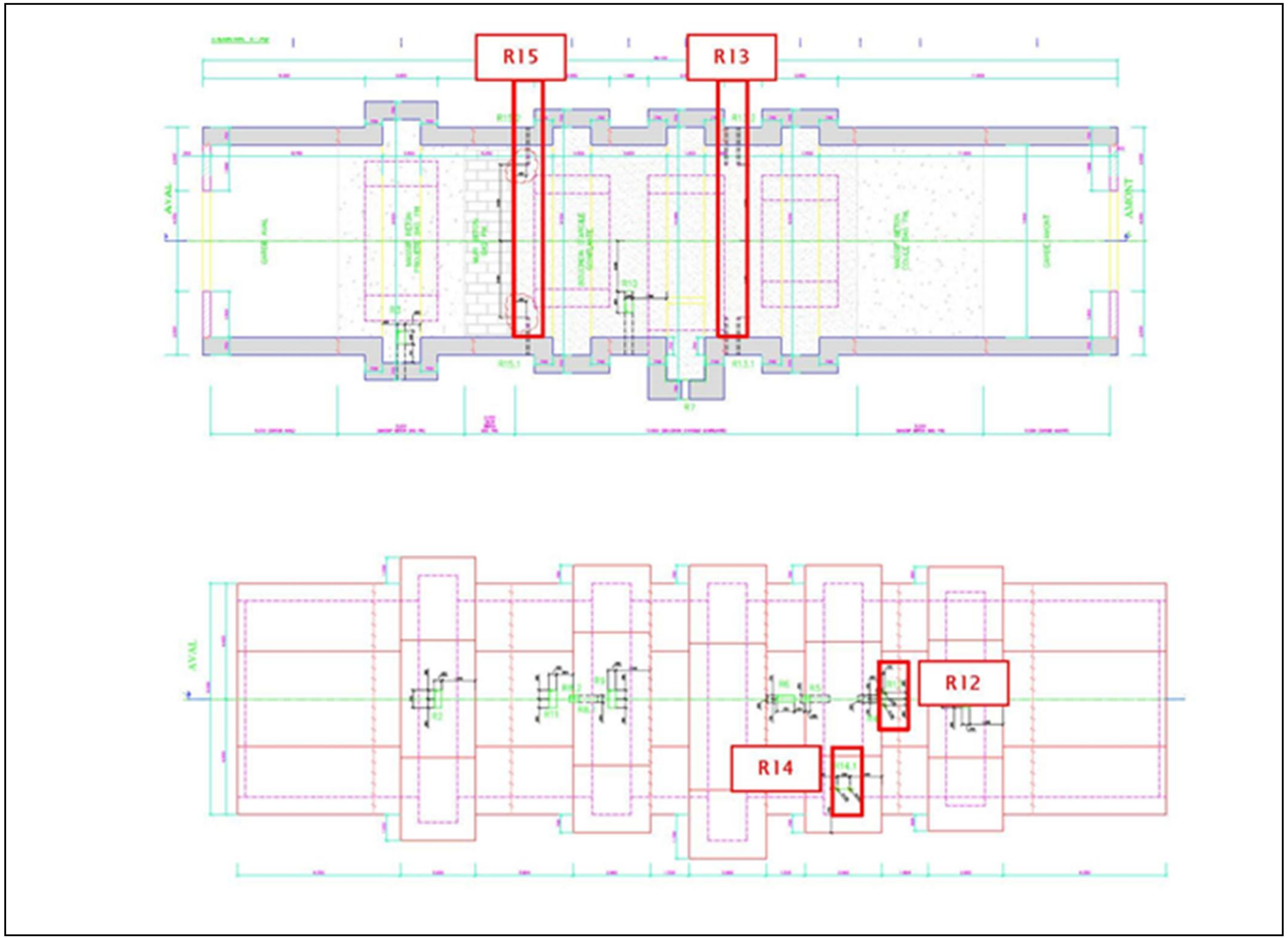



**Figure 4.4**: Location of the different pipes pre-positioned in FSS for gamma-gamma logging of the swelling clay core.

#### 4.4.1 SCC and Shotcrete Containment Walls: Compliance with FSSDS02 and FSSDS03

To monitor the temperature, 16 platinum-based resistance thermometers (PT1000 sensors) in four sections for each type of containment wall were used (Figure 4.3). To measure the strain, 18 strain gauge sensors in three sections for each type of containment wall were oriented in the vertical (Figure 4.3) and horizontal directions. Details of the monitoring system are provided in Noiret *et al*. (2016a and 2016b).

The design specifications for the two containment walls concerning the temperature and strain are (Table 4.1):

- Peak temperature < 50°C (FSSDS02).
- Shrinkage < 350 µm/m at 90 days (FSSDS03).

Example plots showing the measurement of the temperature and strain observed at the Section 1 location (first blue section on the right-hand side of Figure 4.3) for the SCC containment wall and Section 5 (first blue section after the red sections on the left-hand side of Figure 4.3) for the shotcrete containment wall are shown in Figure 4.5 and Figure 4.6, respectively. Measurements at other locations for each containment wall are summarised in Table 4.2 (SCC wall) and Table 4.3 (shotcrete wall).

For the SCC containment wall, the maximum temperature was 48.8°C and the maximum strain was 284 µm/m. Therefore, the requirements for the temperature and the shrinkage at 90 days were fulfilled. It appears that shrinkage, in this case, was mainly a thermal process.

For the shotcrete containment wall, the maximum temperature was 66.7°C and the maximum strain was 633 µm/m. Therefore, the requirements for the temperature and shrinkage at 90 days were not fulfilled. The excessive addition of a hardening additive at the time of spraying is currently considered to be the main reason for the shotcrete temperature being higher than expected. Another possible explanation could be the choice of the "B50 CEM I 52.5 Le Teil" cement, which is a very "reactive" component, and may not be ideally suited to shotcrete application in thick multiple layers. The shrinkage value deviation is probably linked to the heterogeneity appearing at the contact between two shotcrete layers when applied by the operator (poor purging of rebounds).

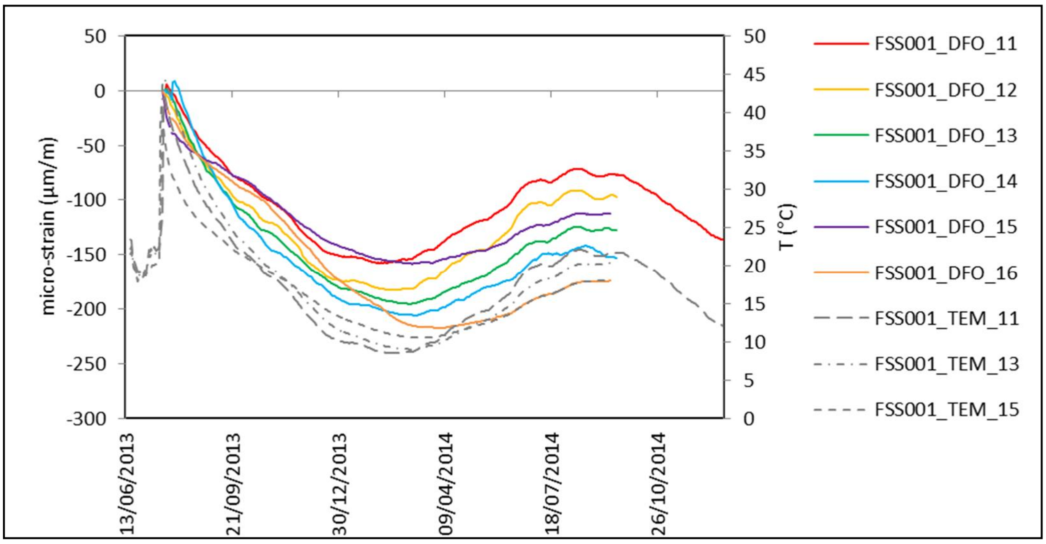



**Figure 4.5**: Temperature (TEM sensors) and strain (DFO sensors) measured for the low-pH SCC containment wall at the Section 1 location.

**Table 4.2**: Maximum temperature and maximum strain measured for the SCC containment wall.

| Location | Maximum Temperature (°C) | Maximum Strain (µm/m) |
|---|---|---|
| Section 1 | 48.8 | 218 |
| Section 2 | 47.2 | 284 |
| Section 3 | 46.9 | Not Available (no data obtained) |
| Section 4 | 46.1 | 257 |

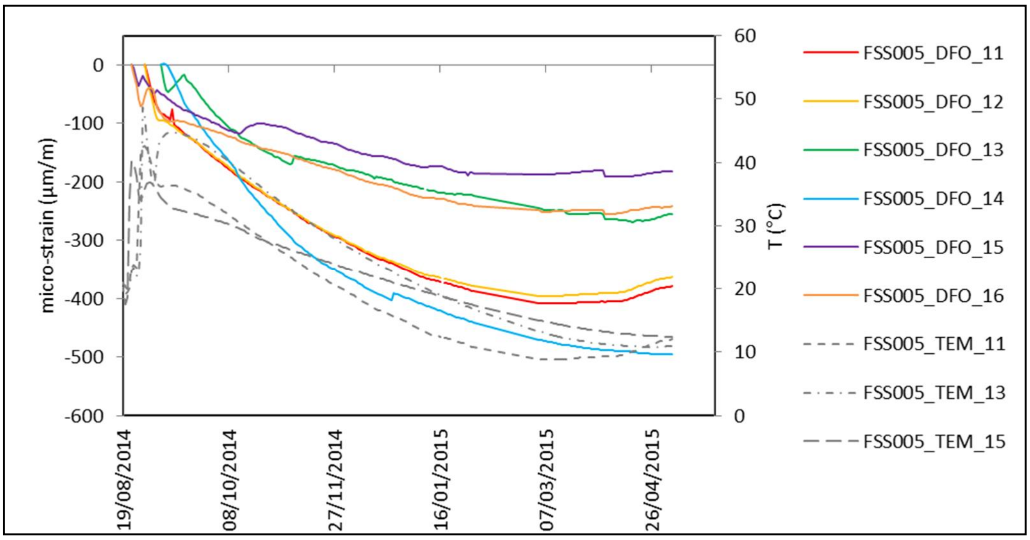



**Figure 4.6**: Temperature and strain measured for the low-pH shotcrete containment wall at the Section 5 location.

**Table 4.3**: Maximum temperature and maximum strain measured for the shotcrete containment wall.

| Location | Maximum Temperature (°C) | Maximum Strain (µm/m) |
|---|---|---|
| Section 5 | 57.9 | 495 |
| Section 6 | 63.7 | 592 |
| Section 7 | 66.6 | Not Available (no data obtained) |
| Section 8 | 66.7 | 633 |

### 4.4.2 Bentonite Swelling Clay Core: Compliance with FSSDS07

In order to compare the emplaced bentonite dry density with the 1,620 kg/m$^3$ design specification and the new specification (1,500 kg/m$^3$) determined at the end of the metric emplacement tests, the density was measured using three methods:

- Mass balance comparison of the emplaced materials with the internal volume of the part of the test box used for the swelling clay core.
- TDR sensor measurements along the profiles shown in Figure 4.3 and further described below.
- Gamma-gamma logs along the profiles shown in Figure 4.4.

In order to provide a comparison with the dry density design specification, the results from the three methods were combined as described below. The results are discussed in more detail in Noiret *et al.* (2016a and 2016b).

*Mass Balance Estimation of Bentonite Dry Density*

The mass balance estimation was done as follows:

- A preliminary 3D scan of the inside of the test box was done at the end of its construction, thus providing an accurate measurement of the total internal volume (including the recesses).
- In order to calculate the residual volume to be backfilled, this 3D scan measurement was repeated again at various stages of the seal construction:
    - After building of the SCC containment wall.
    - After having backfilled the first two thirds of the swelling clay core.
    - After construction of the bentonite core support wall (made of concrete blocks).
- For the bentonite materials, each big bag (of pellets) and each octabin (containing the powder) was tagged and weighed before use.

The average dry density was calculated for the lower two thirds and upper third of the clay core by dividing the mass of emplaced bentonite by the volume backfilled. The average for the entire core was obtained by averaging these values.

*The TDR Measurements*

The TDR technology was used to monitor the quality of the core backfilling. This technology was selected for the following reasons:

- Measurements must be able to detect voids and irregularities in the filling.
- Measurements have to be non-invasive.
- Sensors and accessories should not interfere with the filling process.
- Measurements should be able to resolve small volumes.

The positioning of the TDR sensors inside the test box (periphery) is illustrated in Figure 4.7.

Figure 4.8 shows the effective TDR sensors emplacement inside the FSS test box prior to bentonite mix backfill operations.

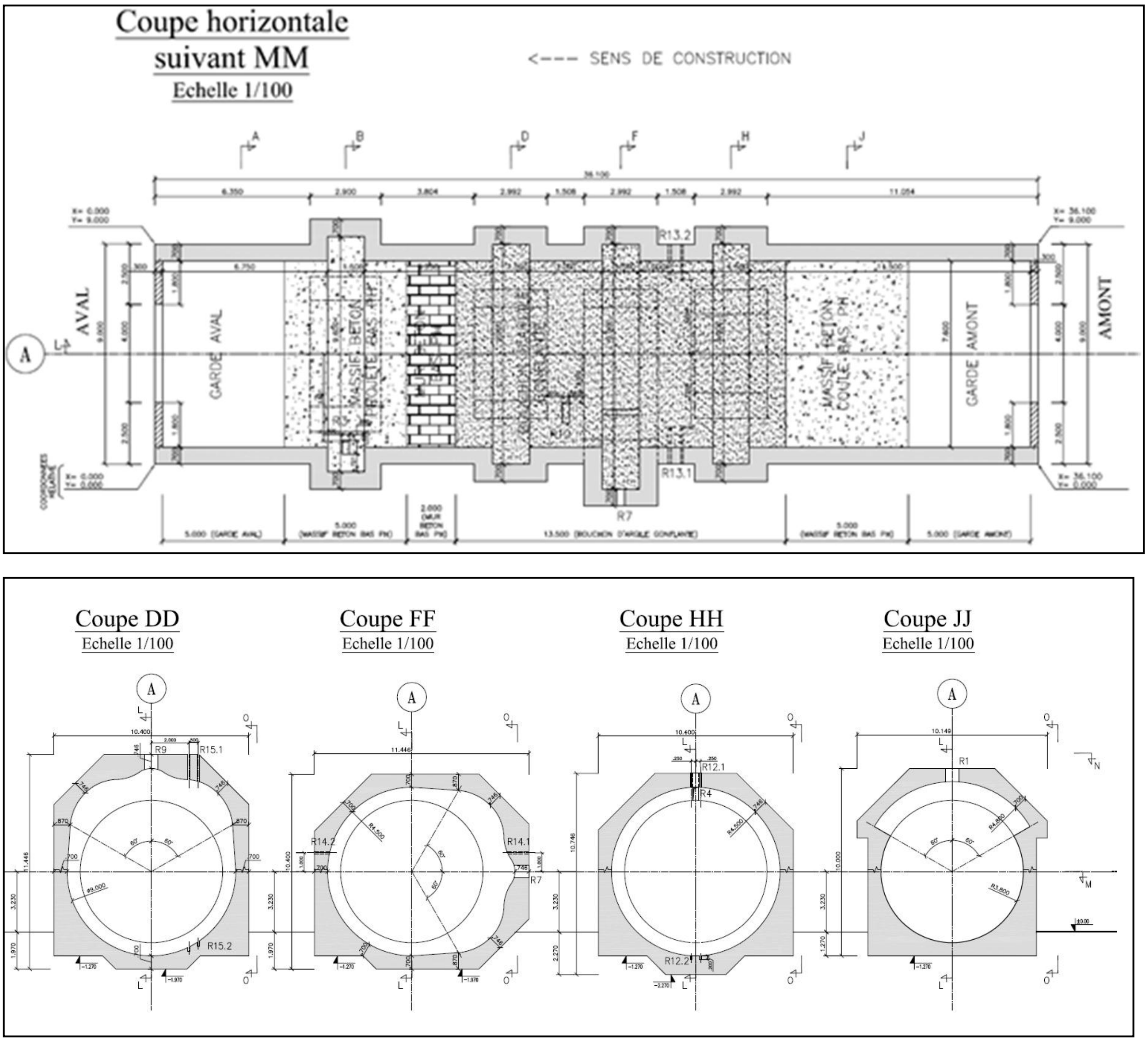



**Figure 4.7**: Longitudinal (top) and sectional (bottom) positioning of the TDR sensors.

**Figure 4.8**: TDR sensors emplacement in a recess (left) and at front of SCC plug (right).

As a basis for interpretation of the TDR results, calibration experiments were initially carried out as part of the bentonite emplacement quality control. The calibration was performed during the metric emplacement tests, principally carried out to validate the backfilling method. Figure 4.9 shows the TDR sensor emplaced inside the metric concrete pipe used for this purpose.

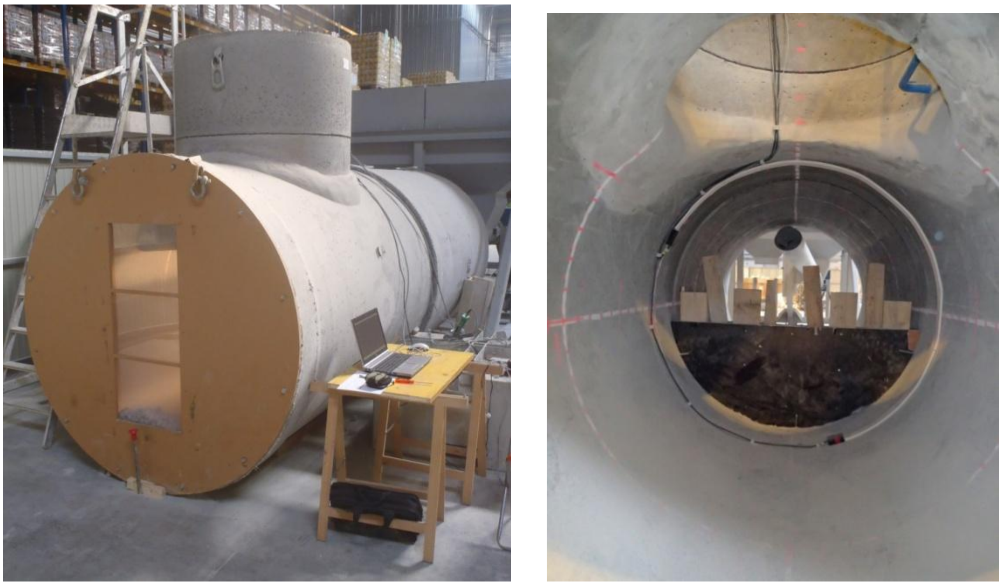


**Figure 4.9**: TDR sensor calibration inside the metric emplacement test pipe.

The results obtained on sections HH, FF, DD and JJ (see Figure 4.7.) are illustrated by images, an example of which is shown in Figure 4.10 for the HH section. Density values are represented by different colours, reflecting the clay core quality detected by the sensors. The following observations are made:

- The backfill density is optimum in the bottom half of the core with a density higher than 1,500 kg/m$^3$.
- The lower part of the top half of the clay core demonstrates a transition in density with a progressive segregation of the bentonite admixture, with the admixture located higher in the core containing more pellets and less powder.
- The upper part of the top half of the clay core contains local voids, where the bentonite is at least 3 cm away from the TDR sensor.

*The penetrometer measurements*

After installation of the FSS test, the emplaced bentonite dry density inside the FSS test box was measured using 10 penetrometer surveys with an average depth or length of 8 m. The surveys were oriented vertically, horizontally or oblique, as follows:

- Six vertical tests performed from the upper platform of the test box.
- Three horizontal tests performed from the side of the test box.
- One oblique test performed from the upper platform of the test box with an angle to the horizontal of approximately 45°.

The length and depth of the different penetrometer tests are summarised in Table 4.4.

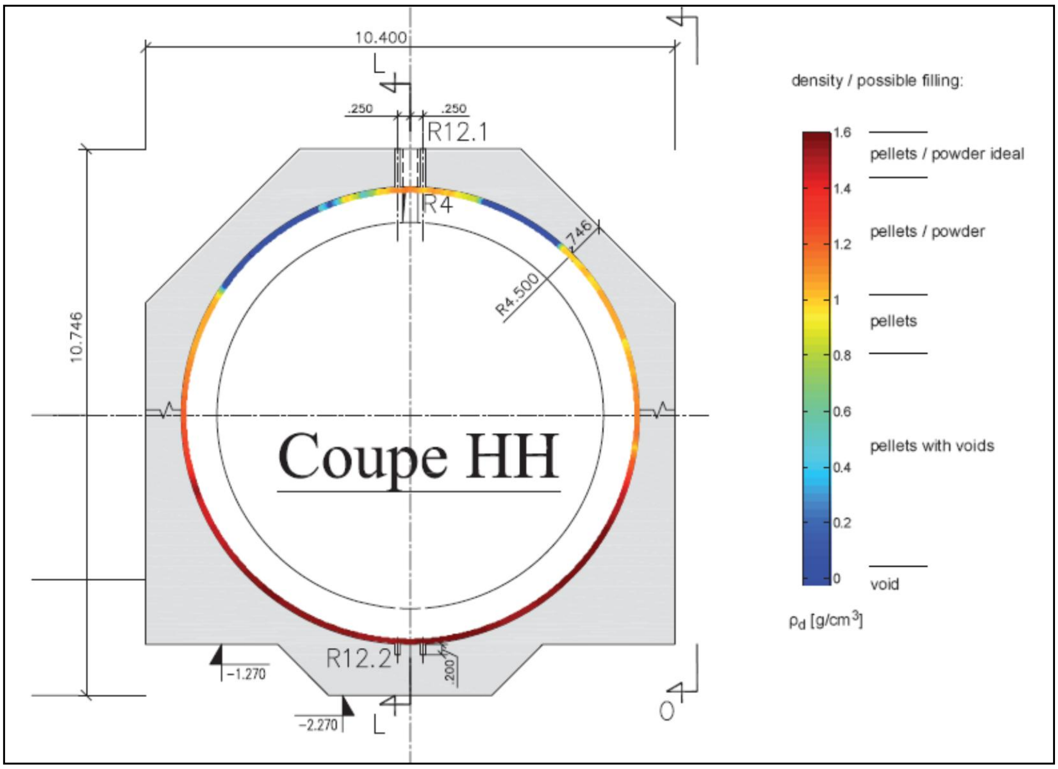



**Figure 4.10**: Illustration of TDR sensors measure of dry mix density at the HH section.

**Table 4.4**: The ten penetrometer tests performed on the emplaced bentonite in FSS.

| N° | Orientation | Angle with respect to the vertical axis (°) | Depth of the penetrometer survey (m) | Length of pre-drilling (m) | Length of material passed through (m) |
|---|---|---|---|---|---|
| SV1 | Vertical | 0 | 8.50 | 0 | 8.50 |
| SV2 | Vertical | 0 | 8.87 | 0 | 8.87 |
| SV3 | Vertical | 0 | 7.24 | 0 | 7.24 |
| SV4 | Vertical | 0 | 7.60 | 0 | 7.60 |
| SV5 | Vertical | 0 | 6.65 | 1.50 | 5.15 |
| SV6 | Vertical | 0 | 8.28 | 0.70 | 7.58 |
| SH7 | Horizontal | 90 | 8.79 | 0.70 | 8.09 |
| SH8 | Horizontal | 90 | 7.86 | 0.70 | 7.16 |
| SH9 | Horizontal | 90 | 8.67 | 0.70 | 7.97 |
| SO10 | Oblique | 45 | 13.56 | 1.00 | 12.56 |

As a basis for interpretation of the penetrometer test results, calibration experiments were carried out as part of the bentonite emplacement quality control. The calibration was performed for the five mixtures of pellets and crushed pellets defined in the specification for the FSS experiment. These concern the following mixtures:

- 100% Pellets.
- 100% Crushed pellets.
- 70% pellets and 30% crushed pellets as used in FSS.
- 85% pellets and 15% crushed pellets.
- 55% pellets and 45% crushed pellets.

For each mixture, five samples with a different density were prepared. For the optimal FSS mix 70:30, densities were centred around 1,500 kg/m$^3$, consistent with the target value of FSS (at a scale of 1:1). Penetrometer tests were then performed on each sample to measure the resistance of the material (in MPa). The relationship between the dry density and the resistance for a given material is defined by a logarithmic function. From the different calibration tests, a linear regression curve of the logarithmic relationship between the resistance value and the dry density for each material was produced (Figure 4.11).

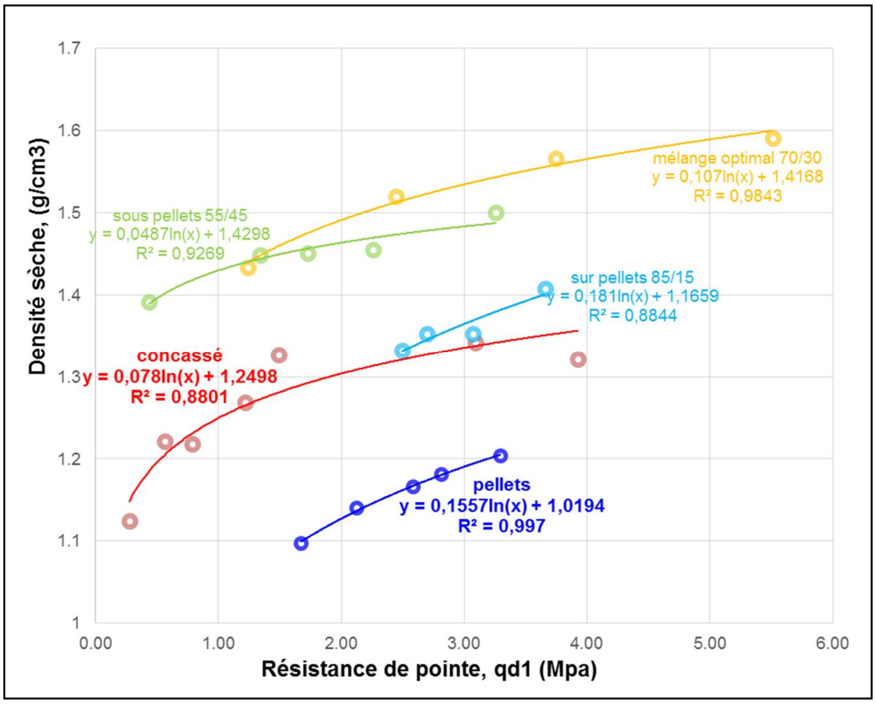



**Figure 4.11**: Calibration curves for the five bentonite mixes tested. The French term "Densité sèche" means "dry density", "mélange" means "mix", "concassé" means "crushed", and "Résistance de pointe" means "resistance of the tip" of the penetrometer.

The application of these calibration curves to determine the spatial variability of the bentonite admixture dry density inside the core is on-going. Additional work is envisaged to validate results and conclude whether this penetrometry device is a practical "commissioning tool" for the future Cigéo operations.

From a qualitative point of view, the penetrometer surveys have also shown that the bentonite dry density is higher in the lower parts of the core than in the recesses at the top of the test box.

This point was confirmed by observation through the polycarbonate windows positioned at the top, on the sides and at the bottom of the test box. The spatial variability in the bentonite dry density is the result of segregation of the admixture as the bentonite is emplaced. In recesses at the top of the test box, only the pellets are present, while the mix is homogeneous at the bottom of the core with no visible voids.

*Gamma-gamma Logging*

The same conclusion, as for the penetrometer results, can be drawn from the gamma-gamma logging campaign. The technology is not mature enough to provide "validated" measurements of the bentonite dry density. From a qualitative point of view, however, the gamma-gamma logging also identified vertical segregation of the bentonite mix between the bottom part of the core and the recesses at the top of the test box.

*General conclusions on bentonite emplacement*

At this stage of research and development, no proven (qualified) tools have been found to accurately determine the dry density of the core bentonite mix and its spatial variability. Additional work is needed in this area.

The gamma-gamma logging tool cannot be a commissioning tool adapted to the *in situ* operations in Cigéo, since pipes cannot be installed and left inside the real and final core. At this stage, additional work is not contemplated on this technology.

The same can be said of the TDR devices which were the only "fully operational tool" adapted to measure the spatial variability of the bentonite dry density.

On the contrary, the penetrometer can be handled underground for horizontal and oblique investigations inside the core volume. Andra is considering further development even if this method is unlikely to be employed in Cigéo.

Practically, the most adapted method to check the density compliance remains the combined use of 3D scanning and mass balance, even if this method only provides average values.

The segregation phenomenon noticed in the recesses at the top of the test box is deemed a marginal point in the swelling clay core behaviour, as the homogenisation of the clay core is expected to increase with saturation. The results of the REM experiment will be very helpful in confirming this expectation.

One practical conclusion from the FSS Experiment is that if additional backfilling of the recesses at the top of the clay core is required in the real Cigéo operations, it is practical to locally use shotclay technology, as practiced in the Czech EPSP experiment. Using such technology, small volumes of bentonite spray can be emplaced accurately into pre-identified residual voids.

### 4.5 Evaluation of the Results from Dismantling of FSS

In this section the observations made at the time of dismantling of the FSS experiment are summarised (more detailed information is available in Noiret *et al.* (2016a)).

- Section 4.5.1 describes the survey and the nature of cracks as observed at the surface of the sawn sections in the two containment walls;
- Section 4.5.2 discusses the quality of concrete.

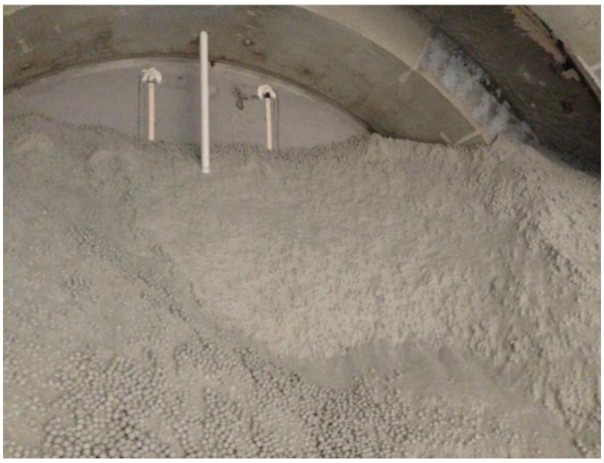
The dismantling activities of the FSS experiment, which took place between August 2015 and December 2015 are illustrated in Figure 4.12.

(a) Coring of the wire sawn low-pH SCC containment wall

(b) Coring of the wire sawn low-pH shotcrete containment wall

(c) Demolition of the low-pH shotcrete containment wall

(d) Demolition of the low-pH SCC containment wall



(e) Removal of the bentonite clay core

(f) Emplacement of bentonite in bags for recycling

**Figure 4.12**: Activities undertaken during the dismantling of FSS.

The dismantling of FSS included coring of the two containment walls. Core samples of 40 cm diameter were taken from the low-pH SCC and shotcrete containment walls for analysis and observation (Figure 4.12 (a) and (b)). After completion of analysis and investigations, the shotcrete and concrete walls were dismantled. This included sawing the shotcrete containment wall longitudinally (i.e., along the test box length) and sawing the SCC containment wall transversally, as shown in Figure 4.13, before demolition using a digger. (Figure 4.12 (c) and (d)). During the dismantling, the bentonite core was removed and placed in bags for recycling (Figure 4.12 (e) and (f)).

The aim of dismantling was to carry out the following investigations on the containment walls:

- Visual inspection and laser measurement of cracks in the concrete containment walls.
- Measurement of surface hardness and sonic velocity to characterise the quality of the concrete.
- Characterisation of surface hardness using an electronic type sclerometer SilverSchmidt.
- Sonic auscultation using a PUNDIT PL- 200 PE Proceq device to determine the sonic velocity, the crack depth, and the existence of defects.

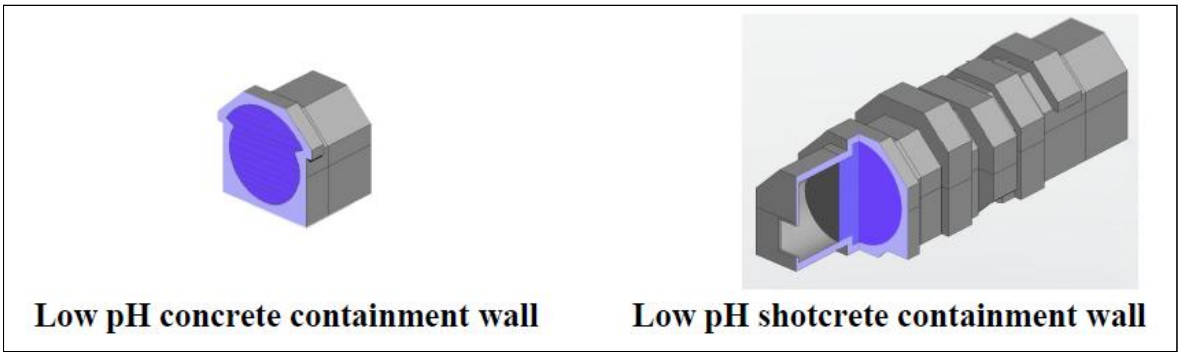



**Figure 4.13**: Sawing of the SCC containment wall (transversally, left) and the shotcrete containment wall (longitudinally, right) in the dismantling activities of FSS.

### 4.5.1 Survey of Cracks

Crack length, aperture and depth were measured at high precision using the laser. The laser was controlled from a scaffold via a touch pad. Figure 4.14 shows the cracks identified in the two containment walls. Subsequently, the cracks were mapped, but the accuracy of the mapping was affected by the presence of the scaffold.

For the low-pH SCC wall, the main observations were:

- Microcracks were identified. The cracks penetrated a few centimetres into the concrete and had an aperture of a few millimetres, i.e. their dimensions were quite limited such that they had no structural impact on the concrete monolith.
- A microcrack was present on the entire perimeter of the SCC containment wall at its interface with the test box. It could not be determined if this microcrack was "penetrating" or simply a surface artefact. In Cigéo, this microcrack, if it appears, would have no practical impact. The progressive rock creeping will lead to a progressive convergence of the drift liner and this convergence phenomenon will have a fretting effect on the SCC containment wall. Besides, the containment wall geometry

is dimensioned based on its interaction with the host rock, not by its friction with the liner wall.

- As mentioned in DOPAS (2016b), only a few litres of contact grouting (less than 100 litres) were injected at the end of the SCC containment wall casting. This grout was locally (less than one square foot) visible and only at the very upper part of the wall, showing a good bonding effect.
- The different concrete pouring passes were not seen, which demonstrates that there was a good adherence of the concrete between the different layers.
- Porosity variations in height were not significant, as confirmed by later measurements on concrete cores.

For the shotcrete containment wall, the following observations were made:

- A microcrack was present on the entire perimeter of the shotcrete. Only the upper part of the demonstrator where the two concretes (concrete box and low-pH shotcrete) seem attached.
- The different layers of shotcrete were visible with variations in density.
- Porosity variations were more significant in the lower part, as confirmed by later measurements on shotcrete cores.

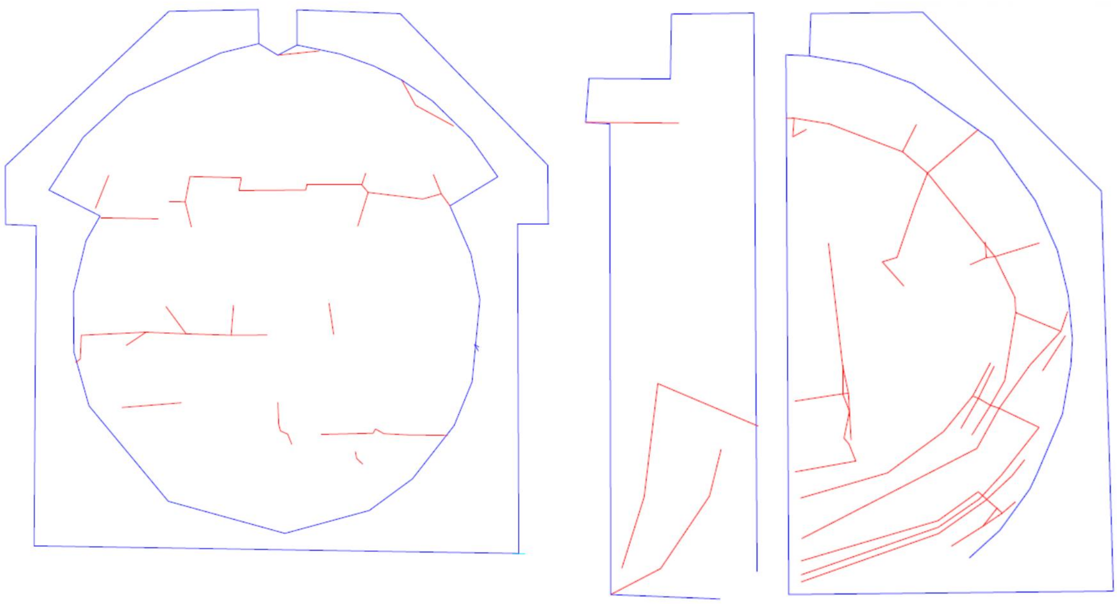


**Figure 4.14**: The pattern of cracks in the low-pH SCC (left) and shotcrete (right) containment walls.

Note that the different patterns of cracks in the SCC and shotcrete walls could be linked to the way the two types of concrete were cast. The SCC was cast in horizontal layers, whereas the shotcrete layers were applied in a hemispherical shape (onion layer type of shape).

More details on the concrete cracking are provided in Noiret *et al.* (2016a).

### 4.5.2 Concrete Quality: Surface Hardness and Sonic Velocity

For concrete, it is established that the bouncing height of an object on concrete increases as the surface hardness reaches higher values (which corresponds in principle to a stiffer concrete). A sclerometer based on this principle was used to measure the hardness of the concrete and shotcrete walls. The sclerometer comprises a flyweight projected by a spring along a rod for transmitting the force to the concrete. The velocity of the piston is measured by the device to determine a rebound number. The rebound number can be processed to estimate the concrete compressive strength through corresponding functions which take into account the type of material, carbonation, and various test conditions.

Figure 4.15 presents the results for the strength (in MPa) of the concrete and shotcrete containment walls.

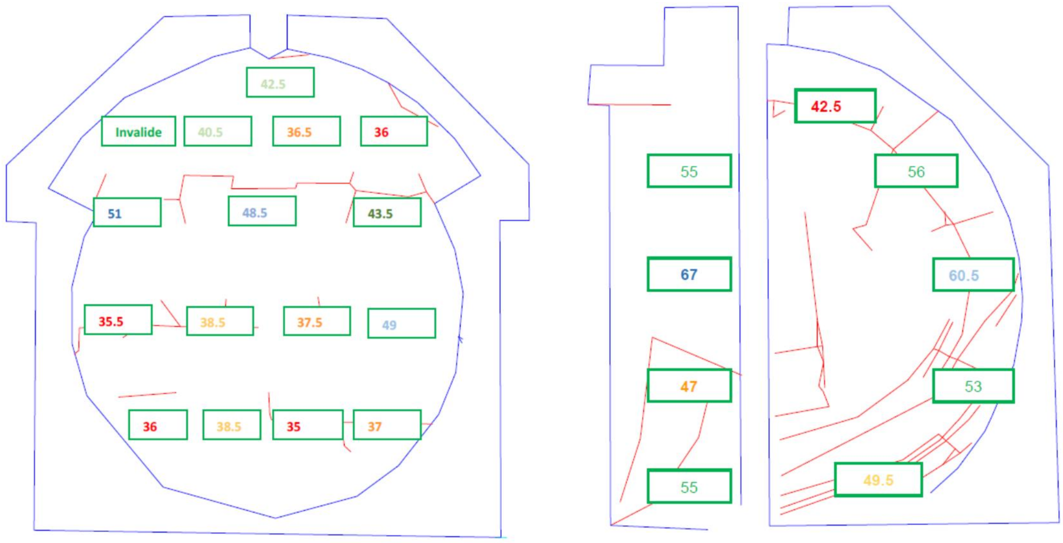



**Figure 4.15**: Results for hardness tests on the concrete (left) and shotcrete (right) containment walls. The numbers indicate values in MPa.

Various measurements were performed to determine the sonic velocity and the existence of defects in the concrete and shotcrete walls. Typically, a concrete can be considered of good quality with a sonic velocity of approximately 4,000 m/s.

The sound propagation speeds measured varied between 2,257 m/s and 3,968 m/s. These low velocities were obtained due to the local presence of a microcrack on the line of the measurements, creating an artefact.

In the SCC wall, the cracks were found to be neither perpendicular nor parallel to the surface and of limited extent, confirming the observations made by laser meter. In the shotcrete wall, a crack depth of up to 5.5 cm was estimated, confirming the heterogeneity of the shotcrete containment wall.

Note that the determination of the physical and chemical properties of the cores taken from the two types of concrete walls is still on going, in various laboratories, at time of writing of this report. All the preliminary results are however coherent with the observations made on the two wall sections. SCC is homogeneous while the variability of shotcrete is quite significant. The concrete mixes and the casting methods are the main causes of the differences observed.

More details on the assessment of concrete quality are provided in Noiret *et al.* (2016a).

### 4.6 Evaluation of the FSS Measurement and Monitoring Systems

This section describes the lessons and preliminary conclusions that can be drawn with regards to the measurement and monitoring systems used in the concrete containment walls and the swelling clay core components of FSS. The measurement and monitoring system is described in more detail in DOPAS (2016b), Noiret *et al*. (2016a and 2016b), and further details on the performance of the FSS system are provided in Noiret *et al*. (2016b).

#### 4.6.1 Measurement systems for the concrete containments walls

Low-pH SCC and shotcrete shrinkage and curing temperature sensors worked well. They could be kept in the Cigéo containment walls as a quality control tool. Intrusive monitoring is not an issue in this case, since the containment walls have no hydraulic performance requirements.

Evaluation of quality of the contact between the host rock and the concrete is challenging. Measuring the volume of injected bonding grout is an indicator of the residual volumes to be filled. Practically, it is probable that 3D scanning before and after casting a containment wall will be the carried out and compared with the measurement of the concrete volume poured inside the form. Besides, the progressive creeping of the rock will ensure a full contact with the concrete before the core swelling induced forces take place, minimising this issue.

#### 4.6.2 Measurement systems for the swelling clay core

Two issues are of concern to commission the swelling clay core:

- Compliance of the measured average dry emplaced density of the bentonite mix with the specified requirements.
- Assessing the space variability of the emplaced mix in the core volume to determine the backfilling heterogeneity, even if no variability parameters have been defined so far by Andra.

On the basis of the works carried-out in FSS, Andra's conclusions on the monitoring / commissioning tools deployed are as follows (see Noiret *et al.* (2016a and 2016b) for further details):

- Penetrometry is a promising solution but is far from ready for application (as calibration is difficult and should be reconsidered for oblique and longitudinal applications). Andra will further explore its development in the future.
- Observation windows: visual observation was difficult at times due to dust build-up on the polycarbonate folio.
- Consistent results from gamma-gamma logging need additional development and a better calibration. Besides, logging requires pipes inside bentonite core, including organic materials. This application to the real Cigéo seals is not considered and no further development is envisaged at this stage.
- For operations, mass weighing of bentonite and 3D scanning will be used in Cigéo.
- No non-intrusive solutions to estimate residual voids have been identified so far. Using the TDR technology is intrusive, even if much less space is needed than for gamma-gamma logging. Andra has not decided yet if this TDR technology will be deployed for the real Cigéo seals.

A parameter-by-parameter evaluation of the monitoring system, is provided in Table 4.5. The monitoring system is described in more detail in DOPAS (2016b) and Noiret *et al*. (2016a).

**Table 4.5**: Evaluation of the FSS experiment monitoring system. Further information is available in Noiret *et al.* (2016a).

| Sensor | Parameter(s) | Evaluation |
|---|---|---|
| PT1000 | Temperature | The sensors were able to track the temperature evolution in various sections of the two concrete monoliths. |
| Vibrating cable<br>Geokon 4200A-2 | Strain in the two types of concrete walls | The sensors were able to track the deformation/strain development in the plugs.<br>Most sensors were able to withstand shotcreting or concrete casting.<br>One set of sensors did not provide data in the SCC monolith. Same situation in the shotcrete monolith. No possibility to say if the failure is due to sensor damage, cabling damage or poor cabling at start-up (QA to be improved in repository operations). |
| TDR Solexperts CSI635_plus | Measure of Dry Mix Density | All the sensors worked well and were capable to show the bentonite mix density variation (segregation) at the ceiling, as confirmed by other investigation tools. |
| **Server** | **Data collected** | **Evaluation** |
| Local Data Acquisition System GeoMonitor | See above + Topographical evolution of test box during filling operations + registering of videos during operations + Relative Ambient Humidity + Relative Air Temperature Humidity | Worked very well, no flaws identified.<br>It was connected via FTP site with Andra Central Data Acquisition System (by SolData), for redundancy in acquisition. |

## 4.7 Assessment of Compliance with the Design Basis and Overall Conclusions from FSS Related to Andra's Reference Drift and ILW Vault Seal

In this section, the results from FSS are discussed with reference to:

- Compliance with the safety functions presented in Section 4.1.1 (and repeated in Section 4.7.1).
- Compliance with the design specifications listed in Table 4.1 of Section 4.1.3 (and repeated in Table 4.6 of 4.7.2), and with respect to general learning obtained during the experiment.

### 4.7.1 Compliance with the Drift/ILW Vault Seal Safety Functions

The safety functions of the drift and ILW vault seals are qualitatively specified as follows:

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

The FSS experiment has provided additional confidence in the ability of Andra to emplace a 1,500 kg/m$^3$ dry density swelling clay core at full scale based on the reference design for drift and ILW vault seals. The density achieved is compliant with the expected hydraulic performance of the seal, although challenges still remain concerning bentonite homogeneity and ceiling voids. These challenges are likely to be resolved by implementing mitigating actions identified in this report. The capacity to emplace a large low-pH SCC containment wall with homogeneous physical and chemical properties was also demonstrated. Thus, this type of material is adapted to sustain the forces induced by the bentonite swelling phenomenon at the time of resaturation.

The FSS experiment has focused on the technical feasibility of reference drift and ILW vault seal. The results from complementary experiments, including the REM experiment (the results of which are reported in DOPAS (2016c) will need to be taken into account in order to demonstrate full compliance with the safety functions.

The compliance of FSS with the safety functions is also met by linking the safety functions to more detailed requirements (design specifications). Evaluation of the performance of the FSS experiment with respect to the design specifications is described in Section 4.7.2.

### 4.7.2 Compliance with Design Specifications and General Learning from FSS

An evaluation of the compliance of the FSS experiment with the design specifications presented in Table 4.1 is presented in Table 4.6. The implications are discussed below.

**Table 4.6**: Compliance assessment for key design specifications on the FSS experiment. The feedback to the design basis is discussed further in the text.

| ID | Requirement / Design Specification | Compliance Assessment | Feedback to Design Basis |
|---|---|---|---|
| FSSDS01 | The pH of the concrete shall not exceed a value of 11, and shall ideally lie between 10.5 and 11 at 28 days. | For the SCC, B50 CEM III/A 52.5 Rombas, B50 CEM III/A 42.5 Héming and B50 CEM I 52.5 Le Teil gave a pH of 11.8, 11.8 and 12.2 respectively after 28 days and a pH of 10.1, 10.2 and 10.3 after 90 days.<br>For the shotcrete, B50 CEM III/A; B50 CEM I; and B40 CEM III/A gave a pH of 11.3, 11.4 and 12.3 respectively after 28 days. B50 CEM III/A and B50 CEM I 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.<br>Note that the "28 days" is not critical – it comes from standard practices in the concrete industry. |
| FSSDS02 | The maximum curing temperature of the concrete and shotcrete of containment walls shall not exceed 50ºC. | For the SCC concrete, the maximum curing temperature was 48.8ºC, and, therefore, the design specification was met.<br>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 (e.g. using CEM 1 rather than CEM III). However, based on the results of FSS, it is likely that SCC will be adopted as part of the reference design for seals. |
| FSSDS03 | The strain as a result of shrinkage of the concrete shall be less than 350 µm/m at 90 days. | For the SCC concrete, the maximum strain was 284 µm/m, and, therefore, the design specification was met.<br>For the shotcrete, the maximum strain was 633 µm/m, and, therefore, the design specification was not met. | As for the maximum curing temperature criterion, based on the results of FSS, it is likely that SCC will be adopted as part of the reference design for seals. |

| ID | Requirement / Design Specification | Compliance Assessment | Feedback to Design Basis |
|---|---|---|---|
| FSSDS04 | Cracking of the concrete shall be minimised to be as small as possible. | For the SCC concrete, only minor cracking was observed, and, therefore, the design specification was met. In addition, the formation of cracks was minimised through the installation procedures (see DOPAS, 2016b).<br><br>For the shotcrete, significant radial cracking was observed, and, therefore, the design specification was not met. | At present, there is no quantitative value available for demonstrating compliance with this design specification and compliance must be judged qualitatively. Further development of the design basis could include development of a quantitative measure of cracking. |
| FSSDS05 | The low-pH SCC shall have a characteristic compressive strength of at least 30 MPa at 28 days and 40 MPa at 90 days. | Measurement of the SCC compressive strength during material development (see DOPAS, 2016b) gave a value of 37.8 MPa after 28 days and 50.7 MPa after 90 days. Therefore, the B50 CEM III/A mix was compliant with this design specification. | The design of the containment walls is not yet finalised, and this design specification is still under development. The current requirement specifies a standard achievable value.<br><br>The strength of the concrete is also linked to the length of the walls which is dependent on other criteria such as technical feasibility and cost. Therefore, although the B50 CEM III/A mix has been shown to be compliant, it is too early to adopt this mix as a fixed part of the reference design. |
| FSSDS06 | The low-pH shotcrete shall have a characteristic compressive strength of at least 25 MPa at 28 days and 35 MPa at 90 days. | Measurement of the shotcrete compressive strength during material development (see DOPAS, 2016b) gave a value of 24±3 MPa after 28 days. Therefore, the B50 CEM I mix narrowly missed compliance with this design specification. | The design of the containment walls is not yet finalised, and this design specification is still under development. The current requirement specifies a standard achievable value.<br><br>Further research may identify suitable materials that could be used to develop a suitable shotcrete mix even if their use underground should be limited and most likely discarded to build a monolith. |

| ID | Requirement / Design Specification | Compliance Assessment | Feedback to Design Basis |
|---|---|---|---|
| FSSDS07 | The dry density of the bentonite materials used in the swelling clay core shall be 1,620 kg/m$^3$. | 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. |

*Implications for the Concrete Containment Walls*

The main outcomes of the FSS low-pH SCC containment wall construction test are:

- The low-pH SCC mix is well suited to pumping and pouring of the monolith, as evidenced by visual inspection of the concrete as it was poured, i.e., the absence of any visible or significant (penetrating) cracks and entrapped air bubbles.
- The concrete pH values and mechanical properties are commensurate with (or better than) the pre-determined specifications.
- The shrinkage values and curing temperature measurements were also within the specifications.
- The operational cycle and the operational tools and methods used are compatible with "Cigéo" underground conditions.
- The SCC containment wall construction was undertaken with existing civil engineering technology, demonstrating that there is no requirement for novel technology developments for emplacement of such structures in a repository.

The result of the shotcreting was observed during operation and was judged to be mediocre since the temperature inside the shotcrete wall reached a higher value than specified (65°C instead of a maximum of 50°C). This high temperature was due to the utilisation of CEM I in the mix which is better than CEM III for spraying as it hardens more quickly, but has a high curing temperature. The following observations on the shotcrete wall were made:

- The shotcrete was far from perfect, with cracks and heterogeneous layers (too much rebound material incorporated to the monolith).
- A new mix for shotcrete needs to be developed in order to have a lower hydration temperature.

- New metric or plurimetric tests need to be implemented in order to optimise the shotcrete emplacement methods.
- Metric cracks with an unknown origin were found in the shotcrete. The bottom part of the shotcrete wall was heterogeneous with poor structural strength. Care needs to be taken when cleaning the rebound. Increasing the mixing time for the shotcrete is expected to lead to better homogeneity.
- The use of shotcrete at large scale is not recommended and should be reserved to layer applications only, when there is a need for a handy use of low-pH concrete and then avoid the burdensome use of a formwork for a small volume.

The analysis work during dismantling has resulted in the following observations:

- Cracks were more numerous and open for the shotcrete containment wall.
- Cracks follow the direction of applying layers for the two containment walls.
- Except for the lower part of the shotcrete wall, no major discrepancies were noted in the shotcrete and SCC. A horizontally and slightly oblique fissure (relative to the sawing plane) was observed on the shotcrete.
- The poor quality of the bottom of the shotcrete is mainly due to the rebounds which were not totally removed by the operator between the spraying of each layer.
- Porosity variations are more significant in shotcrete than SCC. Neglecting the low porosity zones (in the lower part of the wall), resistance of the shotcrete would be higher than the self-compacting concrete.
- The cracking is due to the shrinkage of the concrete. It is important to note that the withdrawal appears in the entire volume of the concrete (in three dimensions). The shape and size of the cracks are influenced by the ratio of dimensions of the containment walls.

*Implications for the Bentonite Swelling Clay Core*

The results obtained from the core emplacement were acceptable despite a longer than expected period of implementation (some nine weeks instead of the planned four). 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$^3$ instead of the expected 1,500 kg/m$^3$. The main reason for the lower value is that the filling machine was too big to move between support wall blocks and completely fill the upper part of the core. In addition, the upper part of the last recess was not filled completely resulting in a gap of around 50 cm.

However, as noted earlier, at this stage of research and development, no proven (qualified) tools have been found to accurately determine the dry density of the core bentonite mix and its spatial variability. Therefore, additional work is needed in this area to further underpin the conclusions regarding the validity of the emplacement method.

Voids in the recesses would be unacceptable in Cigéo. A special procedure must be developed to fill the gaps in the recesses or at proximity of the support wall. Shotclay technology (which employs a small-diameter gun), as used in the EPSP experiment, for the same purpose, is a promising candidate.

The supporting wall, needed to contain the bentonite inside of the core, was built at the same time as the filling operations without any major problem, however, it was quite challenging to complete the construction of the support wall with the augers passing through it at the end of bentonite emplacement operations. To deal with this issue, it will be necessary to develop a specific method to fill the last part of the core. A small-diameter gun, which can be easily moved by hand or by a specific robot, can be used to completely fill the last part of the core volume with shotclay.

The results obtained several months after the end of the core filling in a preliminary œdometric test for REM showed that with a dry emplaced density of 1,510 $kg/m^3$, the swelling pressure obtained was just 3.88 MPa with the argillite (formation) water. This result has to be considered during further development of the seal design to verify if such a dry density could be sufficient to ensure appropriate performance of the clay core. This result has to be confirmed on the long term at the metric scale REM experiment.

## 4.8 Conclusions on the FSS Experiment

The aim of the FSS experiment was to demonstrate the industrial feasibility of the emplacement of large volumes of bentonite (clay core) and low-pH concrete (containment walls) in a full scale seal. Andra is satisfied with the outcomes of the experiment and considers that the GME consortium, who was responsible for conducting the FSS experiment, has demonstrated this feasibility, even though Andra had to revise down the swelling pressure technical specification for bentonite performance (i.e., from 7 MPa to 5 MPa).

Andra considers that construction feasibility is now proven at a one-to-one scale. The low-pH SCC containment wall construction was undertaken with existing civil engineering technology, demonstrating that there is no requirement for novel technology developments for emplacement of such structures in a repository. It was also concluded that low-pH shotcrete use in the repository should be discarded or minimised to be considered only in the building of the support walls or of the surrounding concrete liner support.

The feedback from this construction will be useful in defining the future full-scale seal tests to be conducted at the beginning of Cigéo during the Industrial Pilot Phase. During this Pilot Phase, Andra will build a replica of the future real seal underground, but equipped with various monitoring systems (while no intrusive systems will be allowed inside the real Cigéo seal swelling clay core, at the time of closure).

# 5 SÚRAO Tunnel Plug

This chapter discusses the achievements in the DOPAS Project, in particular the design, construction and pressurisation of the EPSP experiment, with respect to SÚRAO's generic repository programme:

- In Section 5.1, the design basis for the tunnel plugs is described, focusing on the safety functions assigned to plugs, a summary of the reference design, and presentation of the key design specifications contained within the design basis and which are directly tested through measurement of the results of the EPSP experiment. More information on the design basis can be found in White *et al*. (2014).
- In Section 5.2, the EPSP experiment is described, including the objectives of the experiment, and a summary of the design work, construction of the experiment niche and installation of the EPSP components. More details on the construction of the EPSP experiment are in DOPAS (2016b).
- Section 5.3 discusses the learning from the EPSP experiment with respect to the operational issues that will be faced during installation of future tunnel plugs in the repository.
- In Section 5.4, the performance prior to pressurisation of the EPSP components is evaluated, and conclusions drawn regarding the suitability of the materials and the emplacement methods used to install the materials for application in the repository.
- In Section 5.5, the performance during pressurisation of the EPSP components is evaluated, and conclusions drawn regarding the suitability of the materials to provide the necessary performance in a repository.
- Section 5.6 evaluates the performance of the monitoring system used in the EPSP experiment and its applicability in repository monitoring.
- Section 5.7 presents an evaluation of the compliance of the EPSP experiment with the design basis, the feedback of the results to the design basis and discusses the learning outcomes from the work.
- Section 5.8 presents the overall conclusions from the EPSP experiment relating to SÚRAO's reference repository programme.

The information presented in this chapter focuses on a summary of the performance of the experiment. In addition to the further information on the design basis and construction of the EPSP experiment provided in other reports and references therein as indicated above, further details on the EPSP experiment are provided in the EPSP experiment summary report (SÚRAO and CTU, 2016) and the EPSP monitoring data report (Svoboda *et al.*, 2016b).

Modelling of the long-term behaviour of the EPSP plug was not part of the DOPAS Project.

## 5.1 SÚRAO Tunnel Plug Design Basis

### 5.1.1 Tunnel Plug Functions

The first assessment for disposal of spent fuel and HLW in the Czech Republic (SÚRAO, 2012) considered a generic reference concept based on KBS-3V in a crystalline host rock (SKB, 2011). However, subsequent studies have focused on a concept based on horizontal emplacement in disposal drifts within steel supercontainers in a crystalline host rock. Inside the supercontainers, the waste, packaged in steel canisters, is surrounded by compacted bentonite with a steel handling overpack. This concept was the basis for a generic safety assessment in the 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 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.
- To provide a safe environment for workers.
- To provide better stability of open tunnels.

### 5.1.2 Tunnel Plug Design

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 is not highly developed and specific requirements on the reference plug are yet to be 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 5.1).

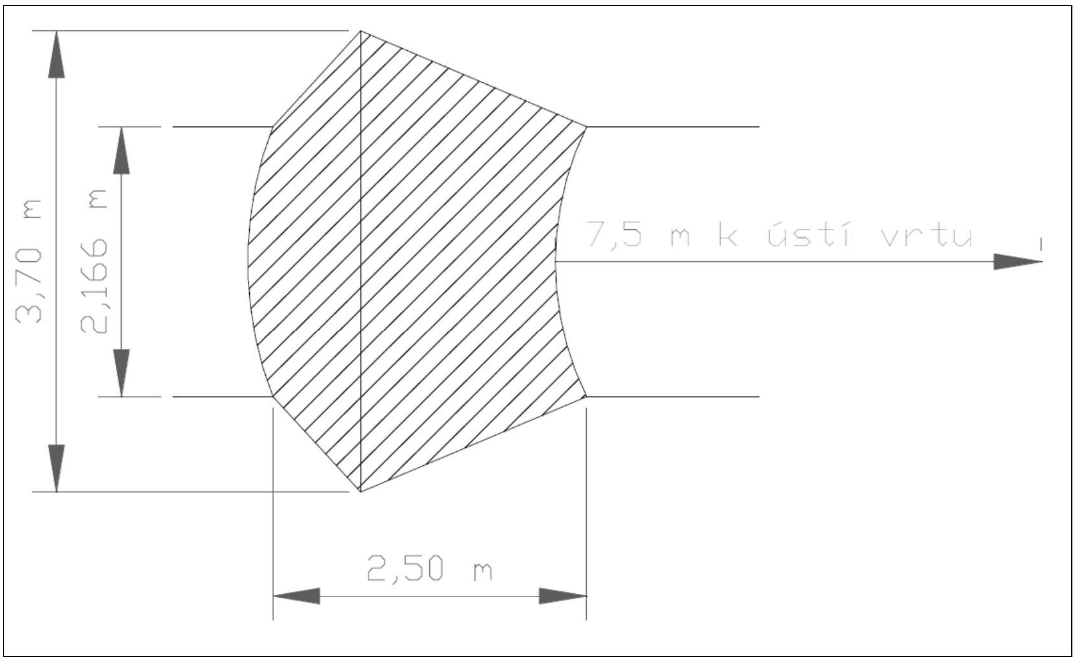



**Figure 5.1**: Schematic illustration of the Czech deposition tunnel plug (SÚRAO, 2012).

### 5.1.3 Tunnel Plug Design Specifications

As demonstrated in Section 5.1.2, the design of tunnel plugs in SÚRAO's reference design has only progressed to the most preliminary conceptual level. Furthermore, as discussed below, the objectives of the EPSP experiment are general, rather than focusing on the further development of reference or alternative designs for the tunnel plug. Nonetheless, a design basis was developed within the DOPAS Project as a basis for evaluating the results of the experiment (see White *et al*., 2014). The key design specifications contained within the design basis and which are directly tested through measurement of the results of the EPSP experiment or during materials development are presented in Table 5.1 (see Section 3.5 for context and justification for the selection of "key" design specifications). More information on the design basis can be found in White *et al.* (2014), including the full set of requirements on the test.

**Table 5.1:** Key design specifications tested through measurement of the results of the EPSP experiment or during materials development as part of the experiment.

| ID | Design Specification | Justification | Compliance Approach |
|---|---|---|---|
| EPSPDS01 | The compressive strength of the concrete shall be a minimum of 30 MPa, with a target strength of 40 MPa. | This design specification is based on the results of design calculations, which take into account the assumed pressure on a plug in a repository (approximately 7 MPa, consisting of 5MPa of pore pressure plus 2MPa of bentonite swelling pressure). These design calculations predict stresses in the concrete plugs to be 20-30 MPa. | Compliance is demonstrated using a static calculation according to Eurocode requirements on concrete strength (Czech standard ČSN EN 1997-1 – design approach 2). In addition, the compressive strength of the selected mix was tested in the laboratory. |
| EPSPDS02 | 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. Potential reactions include the loss of swelling capacity, and changes in porosity, mineralogical composition, or sorption capacity. To minimise these reactions, low-pH concrete must be used.<br>The value of 11.7 has been adopted for the EPSP experiment as an intermediate step towards the development of concrete mixes that generate a low pH leachate, whilst maintaining sufficient strength. 11.7 is considered a reasonable value for the concrete pH at this stage in the Czech programme, with further work required to actually define the appropriate value and a suitable concrete mix to meet the requirement at a later stage. | Measurement of leachate pH during laboratory testing of proposed concrete mixes. |
| EPSPDS03 | The hydraulic conductivity of the concrete shall be less than 1 x $10^{-10}$ m/s. | An appropriate hydraulic conductivity requirement was placed on the EPSP experiment in order to judge the success of the project. For the EPSP experiment, which is focused on development of experience rather than testing of a reference design, there is no specific basis for this requirement, apart from general experience from other disposal programmes. | Samples taken during the installation of the plug were subjected to a permeability test according to the ČSN CEN ISO/TS 17892-11:2005 standard. |

| ID | Design Specification | Justification | Compliance Approach |
|---|---|---|---|
| EPSPDS04 | 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.<br>The value of 60°C has been adopted for the EPSP experiment as an intermediate step towards the development of temperature requirement. 60°C is considered a reasonable value for the concrete temperature during curing at this stage in the Czech programme, with further work required to actually define the appropriate value and a suitable concrete mix to meet the requirement at a later stage. | Monitoring of the temperature using embedded sensors. |
| EPSPDS05 | 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 1 x $10^{-12}$ m/s. The swelling pressure is consistent with swelling pressures assumed in KBS-3 designs and the hydraulic conductivity is a value considered to be readily achievable based on knowledge of the relationship between density and hydraulic conductivity. | Mass balance of emplaced bentonite recorded and average density from known volume calculated.<br>Samples taken during emplacement process. |

## 5.2 Summary of EPSP Experiment

### 5.2.1 Objectives of EPSP

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 (see White and Doudou, 2014; Vašíček *et al*., 2013). 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 will also provide 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, will give indications on crystalline host rock requirements and may support the site selection programme.

The conceptual design for EPSP includes the following components (see Figure 5.2) (White and Doudou, 2014; Svoboda *et al*., 2016a; Vašíček *et al*., 2013; Svoboda *et al*., 2016b):

- 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 pH values were determined during the laboratory testing stage.
- Bentonite Pellets: The bentonite pellet zone is comprised of B75 bentonite (a locally 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. The bentonite zone is 2-m long.
- Filter: The filter collects any water that is not absorbed by the bentonite. This is most likely to occur if the leakage rate across the inner concrete plug is sufficient for piping and erosion of the bentonite to occur. The filter may also be used to reverse the direction of pressurisation of EPSP.
- Outer Concrete 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.

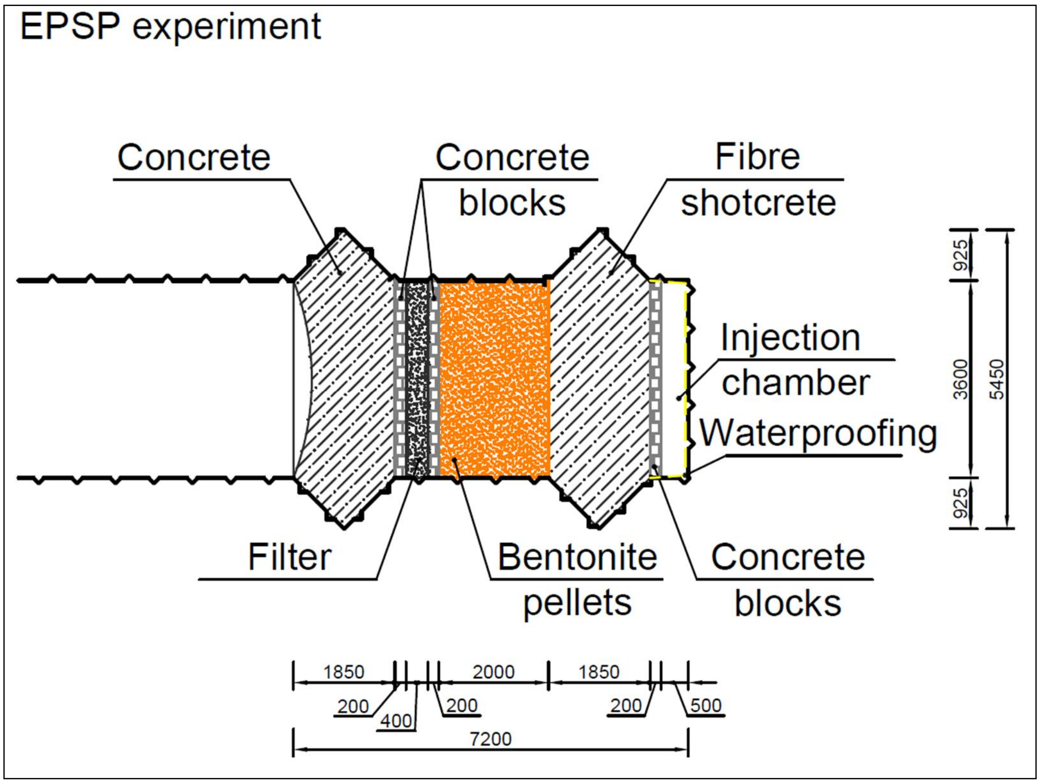



**Figure 5.2:** Schematic illustration of the EPSP experiment design. Dimensions are in mm. Provided by CTU.

### 5.2.2 Summary of EPSP Design and Construction

The design and construction of EPSP included the following activities:

- Materials development and testing to select the concrete mix for the low-pH shotcrete concrete plugs and the bentonite seal.
- Rock grouting, reshaping and ground improvement.
- Installation of the components.

A summary of the materials development and testing, and component installation activities is provided below. Further details are provided in the WP3 summary report (DOPAS, 2016b) and the EPSP experiment summary report (Svoboda *et al*., 2016a) and references therein.

The rock grouting, reshaping and ground improvement activities had to be undertaken due to the specific rock properties of the Josef URC and underground laboratory. This would not be required to the same extent at a repository site, although, of course, grouting, reinforcement and other ground improvement activities are needed as well in repository conditions. However, the rock grouting, reshaping and ground improvement activities were not implemented according to procedures that would be applied in a repository, and, therefore, these activities are not discussed further in this report. More information can be found in Svoboda *et al*. (2016a).

***Materials Development and Testing: Including Compliance with EPSPDS01, EPSPDS02 and EPSPDS03***

At the outset of the EPSP experiment, it was decided to use glass-fibre-reinforced low-pH shotcrete for the Inner and Outer Concrete Plugs. The decision was based on previous experience with iron-fibre shotcrete from the Háje gas storage pressure plugs (Hilar and Pruška, 2011). The alternative of using poured SCC was not adopted because the designers decided that use of shotcreting in the EPSP experiment would provide an alternative to the SCC being tested in other experiments in the project. For EPSP, glass fibres were selected as reinforcement instead of iron-based fibres to avoid the potential for corrosion of the iron-based fibres to affect the post-closure performance of plugs in the Czech repository, and also to avoid the introduction of additional iron into the system. These fibres also significantly help to reduce (micro) cracking from shrinkage.

For EPSP, two low-pH shotcrete mixes were tested in mock-up tests in the Josef URC and underground laboratory, with the preferred mix being selected on the basis of the pore water pH, which was measured to be 11.3-11.5 in the mock-up tests (thereby meeting design specification EPSPDS01), and compressive strength, which was measured to be a minimum of 44.4 MPa (thereby meeting design specification EPSPDS02)[4]. The mixture selected was based on CEM II/B-M 42.5 cement, and contained sand and gravel aggregate, silica fume, glass fibres and additives. The ratio of (micro) silica fume to cement was approximately 1:1 (Svoboda *et al*., 2016a; Vašíček, *et al*., 2014)

One of the main aims of EPSP is to demonstrate the suitability of Czech materials and available technologies for construction of tunnel plugs (see White and Doudou, 2014). Following careful consideration of plug construction requirements, factory-produced bentonite (milled, non-activated Ca-Mg bentonite) was selected as the principal material for the bentonite part of the plug. The commercial product "Bentonit 75" (B75) was the only material available in the Czech Republic at the moment of material selection fulfilling all of the requirements (Svoboda *et al*., 2016a).

Selection of B75 was supported by experience from previous research where B75 was found to fully comply with the required hydraulic conductivity ($\leq 10^{-12}$ m/s) and swelling pressure ($\geq$2 MPa) at a dry density of 1,400 kg/m$^3$ (Trpkošová *et al*., 2013 and Vašíček *et al*., 2016). Testing of the batch supplied for the EPSP experiment confirmed that the batch properties were consistent with the properties of batches previously investigated.

***Installation of the EPSP Components***

The EPSP experiment was installed in following steps:

1 Preparation of the pressurisation chamber <2 m$^3$ (including installation of pressurisation tubing).

2 Treatment of the pressurisation chamber with waterproofing.

3 Installation of the first concrete separation wall between the pressurisation chamber and the inner plug.

4 Installation of the inner plug using glass fibre low-pH shotcrete.

5 Installation of sealing core, filter and auxiliary structures (concurrent process):

[4] Further testing of the compressive strength of the concrete will be undertaken during the dismantling of the test. This testing will be used to evaluate the representativeness of the laboratory and mock-up test measurements.

a. Emplacement of the bentonite sealing material.

b. Installation of the second concrete separation wall between the bentonite and the filter.

c. Installation of the filter material.

d. Installation of the third concrete separation wall between the filter and the outer plug.

6 Installation of the outer plug using the same material used for the inner plug.

Monitoring instrumentation was installed gradually as construction progresses.

The installation of the experiment is summarised in more detail in DOPAS (2016b) and Svoboda *et al.* (2016a).

## 5.3 Learning Related to Operational Issues

The learning from the installation of EPSP includes the following (further details are provided in DOPAS, 2016b and Svoboda *et al*., 2016a):

- The place for the plug installation had to be carefully selected. The quality of the rock must be consistent with the expected pressures developed by swelling of the bentonite seal, without any located disturbance.
- The process of the plug construction must be integrated to the time schedule of the building repository and operation. The supply of fresh concrete and bentonite materials must be capable of meeting the requirements of the repository schedule during the operational period. Transport and storage of all materials must be consistent with the safety requirements. Proper logistics is crucial.
- During the construction of the plug (concrete and bentonite emplacement) fresh air must be provided and contaminated air must be extracted from the working place by the dedicated lines because of dust evolution. The construction area should be separated from operated part of repository.
- The use of sprayed shotcrete for concrete plugs was considered to be successful in EPSP despite the presence of some challenges. The advantages of spraying shotcrete include: no need for an outer formwork leading to quicker preparation activities, no issues with uneven surfaces or formwork tightness. Some of the disadvantages of using spraying technology include: dust generation, need for continuous clean-up resulting from rebound, the dependence of the quality of the structure on the nozzle operator skills, and the need for additional equipment (i.e., a spraying machine).

## 5.4 Evaluation of Performance of EPSP Components Prior to Pressurisation

In this section the performance at the time of installation of the EPSP experiment with respect to the design specifications listed in Table 5.1 is evaluated:

- Section 5.4.1 discusses the monitoring of the performance of the sprayed fibre concrete, which contributes to the compliance assessment for EPSPDS04.
- Section 5.4.2 discusses the monitoring of the bentonite seal section, which contributes to compliance with EPSPDS05.

The system used to measure and monitor the installation of EPSP is described in DOPAS (2016b), and Svoboda *et al*. (2016a) and references therein. Svoboda *et al*. (2016a) provides a more extensive discussion of the performance of the EPSP experiment.

Prior to pressurisation of the EPSP components, it was considered that the glass-fibre-reinforced low-pH shotcrete was successfully installed for the inner and outer concrete plugs. Glass fibres were used to limit crack formation and to improve the strength of these structures without using pre-placed reinforcing. The low-pH concrete was used to limit possible impacts on bentonite. Contact grouting was needed to prevent leakage on the contact zone between the plug and the host rock. Bentonite B75 was considered to be a suitable material for plugs and seals and the combination of vibration compaction and shotclay technology of bentonite pellets proved to be a viable approach for bentonite sealing installation. More detailed discussions on the concrete plugs and the bentonite section are provided below.

### 5.4.1 Sprayed fibre concrete plugs

The inner and outer shotcrete lugs were erected in the same manner. The composition of the final concrete mixture was as follows (with a microsilica/ cement ratio of roughly 50/50):

- Cement CEM II / B – M (S-LL) 42,5 N
- Sand & gravel 0-4 & 4-8 Dobřín
- Plasticiser SIKA 1035CZ
- Retardant SIKA VZ1
- Accelerator SIKA Sigunit L93 AF
- Microsilica SIKA FUME
- Glass fibres – crack HP (Sklocement Beneš)

As described below, the concrete mix performed well in terms of workability, emplacement and later on when it cured. The 12 hour workability proved to be useful giving enough buffer time for transport to the Josef facility, reloading into smaller trucks, transporting to the emplacement location and then emplacement. No segregation was detected during transport.

The shotcreting behaviour was good and was the same as with “ordinary” shotcrete mixtures. The sprayed shotcrete stuck well to the surface with rebound equal to or less than with “ordinary” shotcrete mixtures. The dust evolution was noticeably lower than with “ordinary” shotcrete mixtures.

The glass fibres were introduced during the production of the concrete. The glass fibres caused no issues for emplacement, as no glass fibre accumulation or clogging was detected.

Overall performance during emplacement was good with low levels of dust. The main advantages and disadvantages are generally the result of the shotcrete technology (see Section 5.3).

The performance of the shotcrete plugs during curing was consistent with the design specifications established for the plug. The results of the monitoring of the curing temperature are shown in Figure 5.3. As shown in Figure 5.3, the maximum temperature reached inside was approximately 55°C, which is consistent with requirement EPSPDS06. At this temperature, significant cracks will not form in the concrete and shrinkage will be minimised. Shrinkage has been monitored by measuring the strain in the concrete Figure 5.4, which shows that the shrinkage is small (<0.3%). In addition to monitoring of the temperature and shrinkage, visual inspection of the concrete confirmed that the only cracks formed were between the shotcrete sprayed on the sides of the niche and the plug bodies. This indicates that the body of each plug shrunk in one piece while probably separating to some extent from the rock surface.

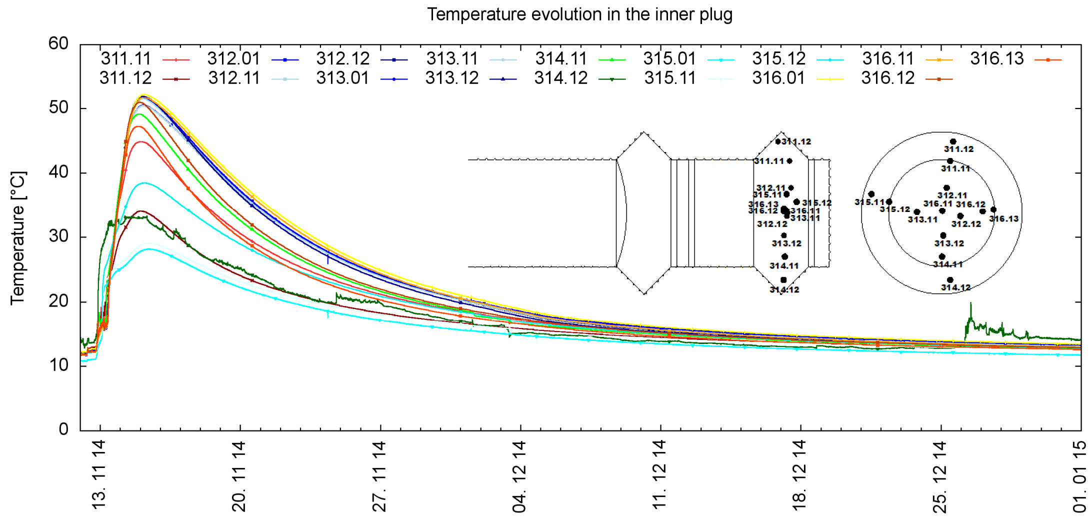



**Figure 5.3:** Results from monitoring of the temperature inside the inner plug during installation and curing. The location of the monitoring sensors is also indicated.

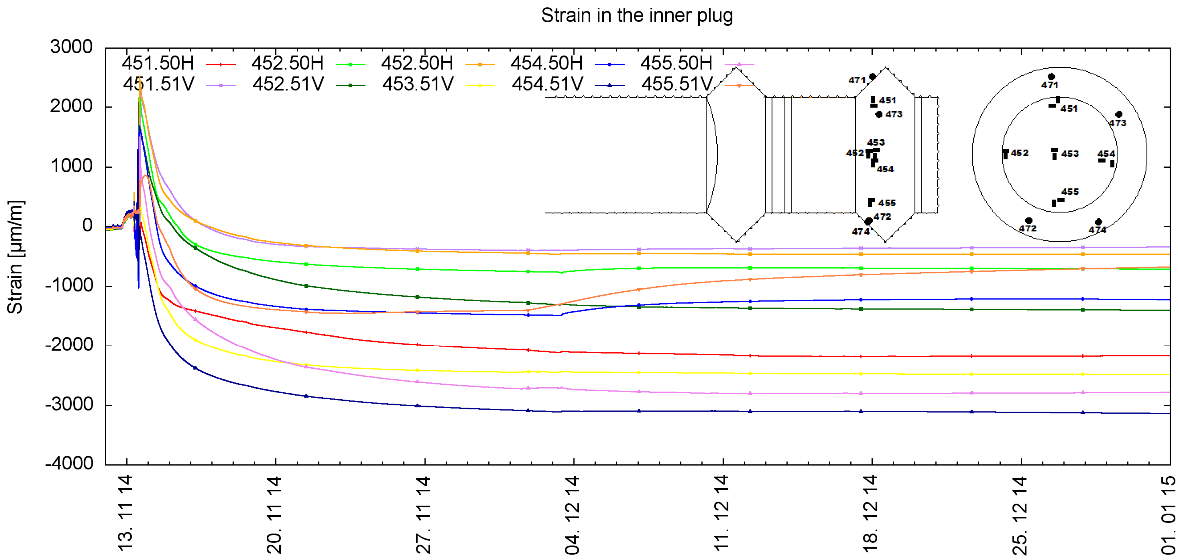



**Figure 5.4:** Results from monitoring of the strain inside the inner plug during installation and curing. The location of the monitoring sensors is also indicated.

The inner plug has been tested for tightness by water and air after curing by gradually increasing the pressure to 0.6 MPa. An excessive leak, defined as a steady flow of water, was detected in the contact zone between the plug and the rock, therefore grouting of this interface was undertaken. The following main factors causing the leak were identified:

- Separation of the plug body from the rock due to shrinkage.
- Failure to fully seal the EDZ (especially close to the plug-rock interface).

- Weaker concrete on the contact with the rock, possibly including leftovers of uncleaned rebound or “shadows”[5].

The above list is sorted from the most significant to the least significant factor according to the observations made and expert judgement. However, no exact quantification can be made without experiment dismantling.

The test also revealed that some rock fractures believed to be closed and sealed by previous grouting were reopened by the pressure test, based on the observation of leakages from these fractures.

There were no grouting pipes pre-installed before the inner plug erection. Therefore, the grouting was performed by drilling boreholes into the contact zone with subsequent injection of grout into them. Several campaigns were performed until the leakage was reduced to a few drips (a certain amount of leakage had to be left in order to be able to test bentonite sealing). Escapes of grout media from the rock in the vicinity of plug were observed supporting the suggestion in the list above that the EDZ was not fully sealed.

The experience gained from the inner plug resulted in installation of grouting pipes in advance of outer plug erection into contact zone of outer plug. The outer plug was primarily grouted using this piping. An additional grouting was later on performed based on results of a pressure test (side effect of bentonite sealing activation by water from filter structure) of the outer plug in the place where leaks were detected. This was done in similar way as for the inner plug by drilling grouting boreholes into the contact zone where necessary.

It is considered that the weakest point of the fibre shotcrete plug structures is the wider contact zone between the plug body and the rock mass. The effect of this weak point can be mitigated by grouting of the interface. It is strongly recommended to have these measures prepared in advance – e.g., grouting pipes installed in the plug/rock contact zone.

#### 5.4.2 Bentonite sealing section

B75 bentonite is produced in powder form which is not ideal for sealing plug purposes owing to the low density of the raw material. Therefore, the first stage involved the selection of the best compaction technology commercially available in the Czech Republic. As described in DOPAS (2016b), two methods were selected:

- Roller compaction, which was used to produce pellets for the main part of the bentonite seal.
- Roller milling, which was used for the small volume of bentonite emplaced at the top of the seal using shot clay technology.

The construction of the EPSP bentonite pellet sealing section was done in nine days in June 2015. The lower parts (over 95% by volume of the bentonite component) were emplaced in horizontal layers. Each layer was vibration-compacted using a compaction plate (NTC compaction plate, Masalta vibration plate) or electric hammers. This emplacement technique proved to be quick and can be easily scaled to an industrial level. The dust generation was low. The drawback is that it has problems in the upper parts of the gallery where the machinery does not fit. Therefore, shotclay was used for the upper parts of the bentonite seal.

[5] Shadows are parts of the sprayed concrete that have been affected by obstructions during the spraying process, for example areas of a concrete wall behind monitoring system cables. Owing to the influence of the obstructions, the sprayed concrete may be of lower strength.

The sprayed upper part of the bentonite seal contributed approximately 3% to the total volume of the seal, and, as noted above, was emplaced using shotclay technology. The spraying machine selected was SSB 14 DUO (Filamos Ltd.) with electric air compressor Atlas Copco (working pressure 10 bar, air capacity 350 $m^3$/h). These machines were tested in a pilot test before usage in EPSP.

The shotclay technology was implemented successfully. The main advantage is the ability to fill up confined and irregular spaces. However, there are some drawbacks: the throughput is lower compared to other methods, it is operator-dependent, rebound has to be cleared and there is relatively high dust generation.

The total amount of emplaced material is 39.9 tonnes which was placed into volume of 23.7 $m^3$. The achieved average density was 1,684 kg/$m^3$ and the dry density was 1,427 kg/$m^3$. The differences in the dry density between the vibration compacted section and the shotclay section were not judged to be significant, although precise measurements of the two densities were not feasible during installation.

Generally due to size constrains, only small machines were used during bentonite emplacement in EPSP. In a repository, it is expected that full-sized machinery with higher throughput would be used.

## 5.5 Evaluation of Performance of EPSP Components during Pressurisation

In this section the performance to date of the EPSP experiment following pressurisation is evaluated. Figure 5.5 shows the pressurisation sequence of the experiment up to the end of March 2016. At this stage, only initial pressurisation had been undertaken; the final pressure applied to the experiment is expected to be 4 MPa (consistent with the DOMPLU experiment), but this will depend on the outcomes of the earlier stages of the experiment.

As summarised in Section 5.4, experimental testing of EPSP started during the construction process. The inner plug was pressurised through injection of water and air into the injection chamber up to 0.5 MPa to check the water tightness of the concrete and to determine if grouting was needed.

Once the outer plug had cured, the main experimental activities started with 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). At 1 MPa a possible channelling of the bentonite seal was detected. At this time, the swelling pressure in the bentonite had not yet fully developed.

In order to avoid erosion of the bentonite, the testing sequence was interrupted and the sealing section was saturated by injection of water in both the filter and the pressurisation chamber to allow swelling pressure to develop. Saturation started at low pressure and was gradually increased to just over 1 MPa.

Following the saturation of the bentonite, a short pressure test was undertaken involving injection of bentonite slurry into the pressurisation chamber at pressures up to 3 MPa. The pressurisation chamber was then cleaned up, and pressurisation of the experiment using water pumped into the pressurisation chamber resumed.

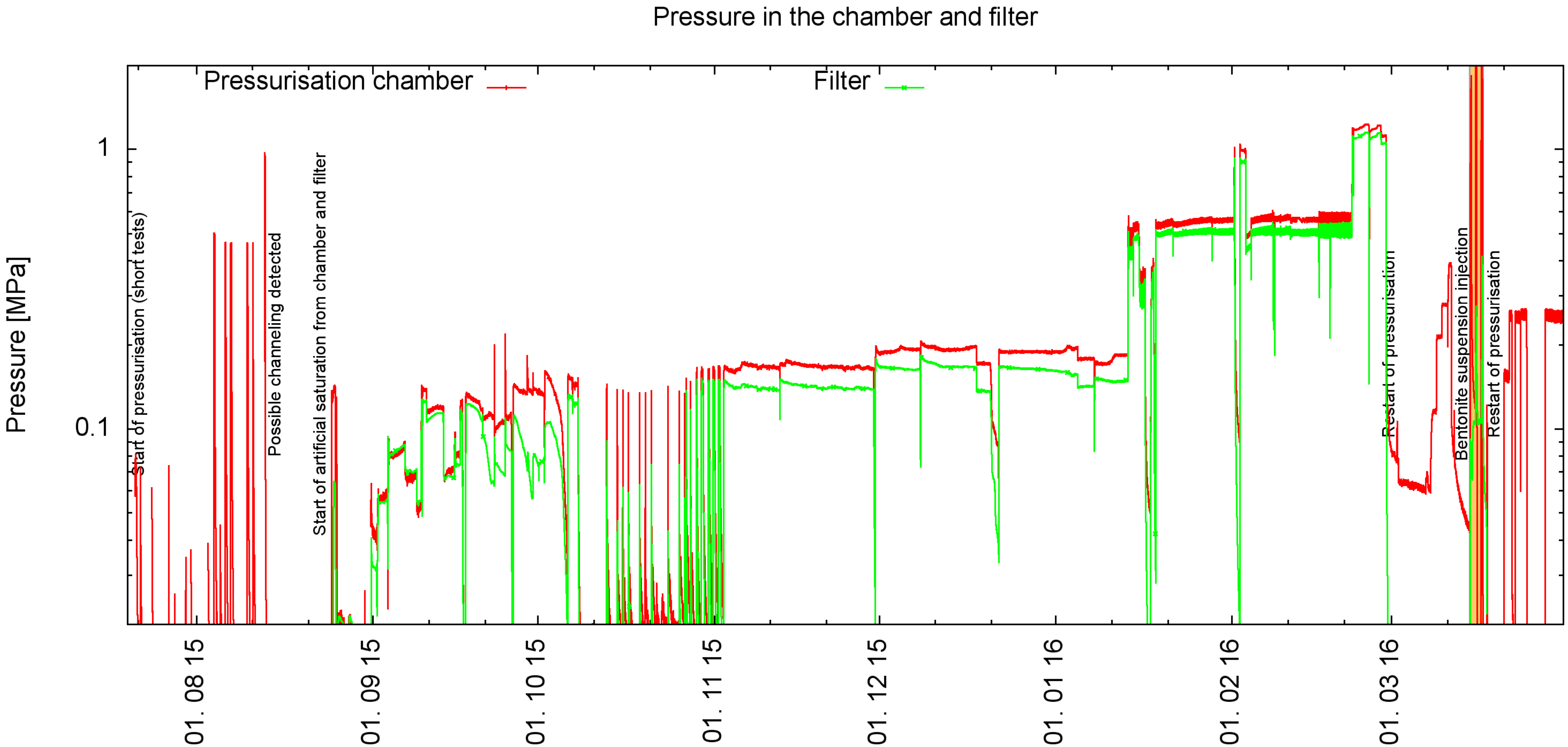



**Figure 5.5:** EPSP pressurisation sequence.

As the EPSP is focused on development of knowledge and experience, no performance criteria have been identified for the plug at the current time in the Czech disposal programme. Instead, parameters have been monitored to develop the understanding of the performance of the plug during pressurisation (see DOPAS, 2016b for a justification for the selection of the monitoring parameters):

- For the sprayed fibre concrete plugs (Section 5.5.1), strain, temperature and water flow rate have been monitored.
- For the bentonite seal (Section 5.5.2), total pressure, flow rate, relative humidity, and water content have been monitored.

### 5.5.1 Sprayed Fibre Concrete Plugs

The sprayed fibre concrete plugs have performed well during all of the pressure tests undertaken to date. No structural damage has been recorded. The plugs exhibited limited strain in response to all of the pressure loads, including the loads exerted from the pressure chamber and from the filter (Figure 5.6). The strains measured in response to pressurisation to date have been significantly lower than the strains resulting from shrinkage during curing. The hydraulic behaviour of the EPSP experiment in response to pressurisation has been consistent with the design specification. No leakages through the concrete plugs and bentonite seal have been detected. However, as described above (Section 5.4) the contact zone between the plug and the rock was a weak spot where leakages had to be treated by grouting. The weak contact zone limited the usefulness of the concrete plug to reduce flow into bentonite sealing layer.

### 5.5.2 Bentonite Sealing Section

Testing of the bentonite sealing section started with the pilot run of the experiment at low pressure (as described above) followed by tests at higher pressures.

One of the higher pressure tests on non-swelled ("dry") sealing led to flushing of traces of bentonite at one point of the test. The origin of bentonite could not be fully determined. Two origins for the bentonite are considered possible: the filter, which may have become contaminated by bentonite during emplacement of the bentonite seal (especially during shotclaying); or erosion of the bentonite seal during the pressurisation of the experiment.

The character of the flow and bentonite content indicated that water (without bentonite) probably travelled most of the time along a fracture (opened by the high pressure) in the rock before entering the filter structure. The major part of bentonite detected was therefore most likely to have come from the filter (contamination flushed out by water).

Evaluation of the performance to date has mainly focused on the period during the injection of water in both the filter and the pressurisation chamber. The performance of the bentonite seal is as expected. Monitoring of total pressure has demonstrated that swelling of the bentonite seal commences from the outer part of the seal first as the bentonite saturates (Figure 5.7). The self-sealing ability of the bentonite has been indirectly detected by the monitoring system at several places where water quickly entered to the sensor along cabling and later on "disappeared", indicating that the water flow path was closed and water absorbed by bentonite.

The monitoring of saturation of the bentonite seal is shown in Figure 5.8 and Figure 5.9. The self-sealing behaviour is most clearly illustrated by the spike in water content that occurred in August 2015, and is shown by the red curve in Figure 5.9.

Monitoring of the pore pressure development in the bentonite seal during the initial pressurisation of the EPSP experiment is shown in Figure 5.10. The distribution and development of pore pressure indicate that the contact zone between the plug and the host rock (including the EDZ) is providing a pathway for relatively rapid propagation of pressure - the sensor located close to the concrete plug at the experiment rotational axis shows almost no reaction to the pressurisation but sensors on the sides do. This indicates that there is no direct connection through the shotcrete – i.e., it performs well. A similar performance in response to pressurisation is illustrated in the other profiles where the bentonite/rock interface reacts fast but the reaction in the inside of bentonite is much smaller/slower or almost nothing.

The swelling pressure development can be followed on absolute pressure graph (Figure 5.7). When pressurisation is interrupted (illustrated by the red line being approximately zero in the bottom graph of Figure 5.7, for example during October 2015) the residual absolute pressure represents swelling pressure. Swelling can be confirmed when the absolute pressure exceeds the pore pressure. For example, the swelling pressure is around 100-200kPa with some sensors (e.g. sensor 878 in Figure 5.7) starting to show higher levels of swelling in March 2016.

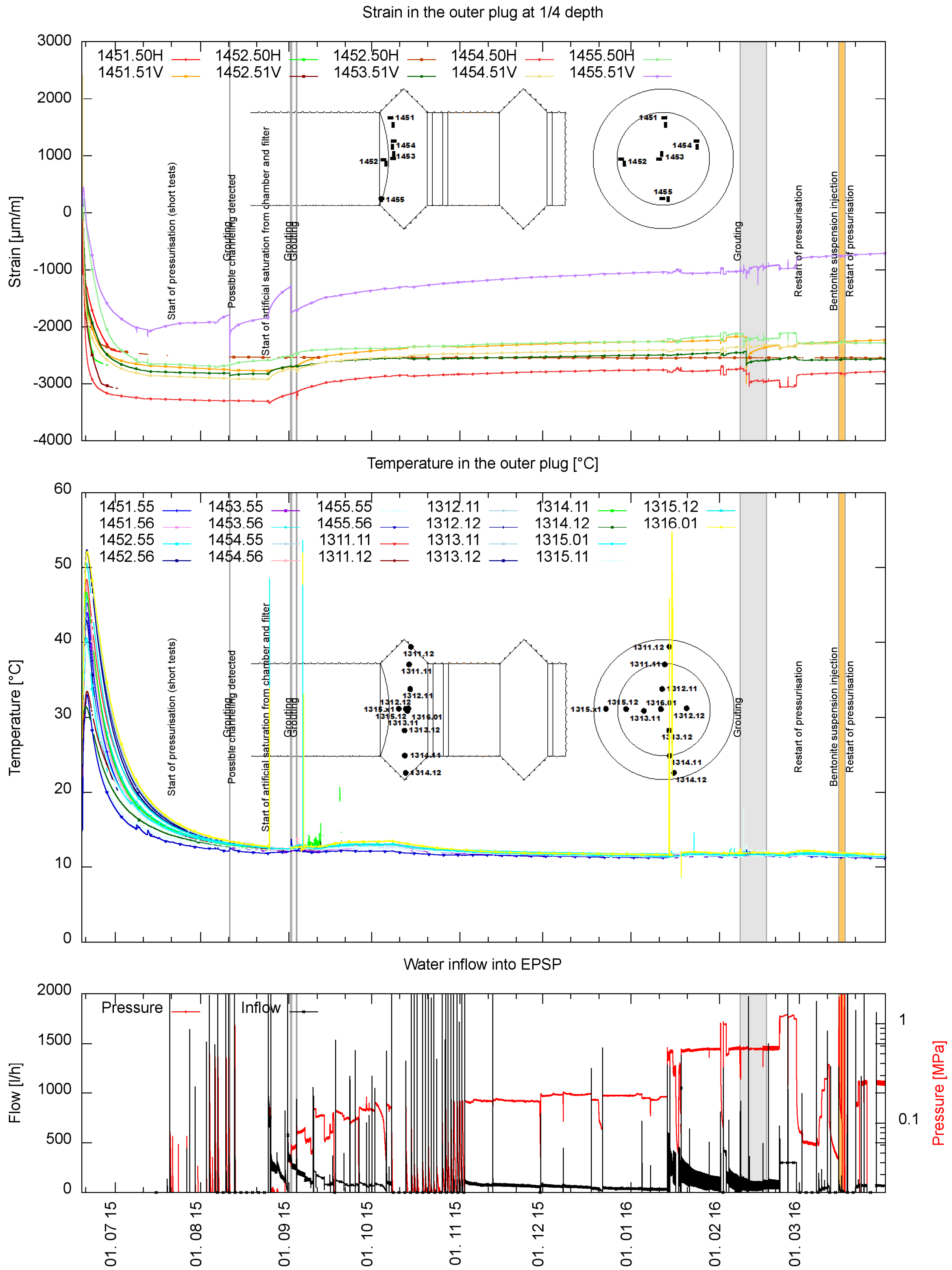



**Figure 5.6:** Strain, temperature and water flow for the outer plug in response to pressurisation of the EPSP experiment.

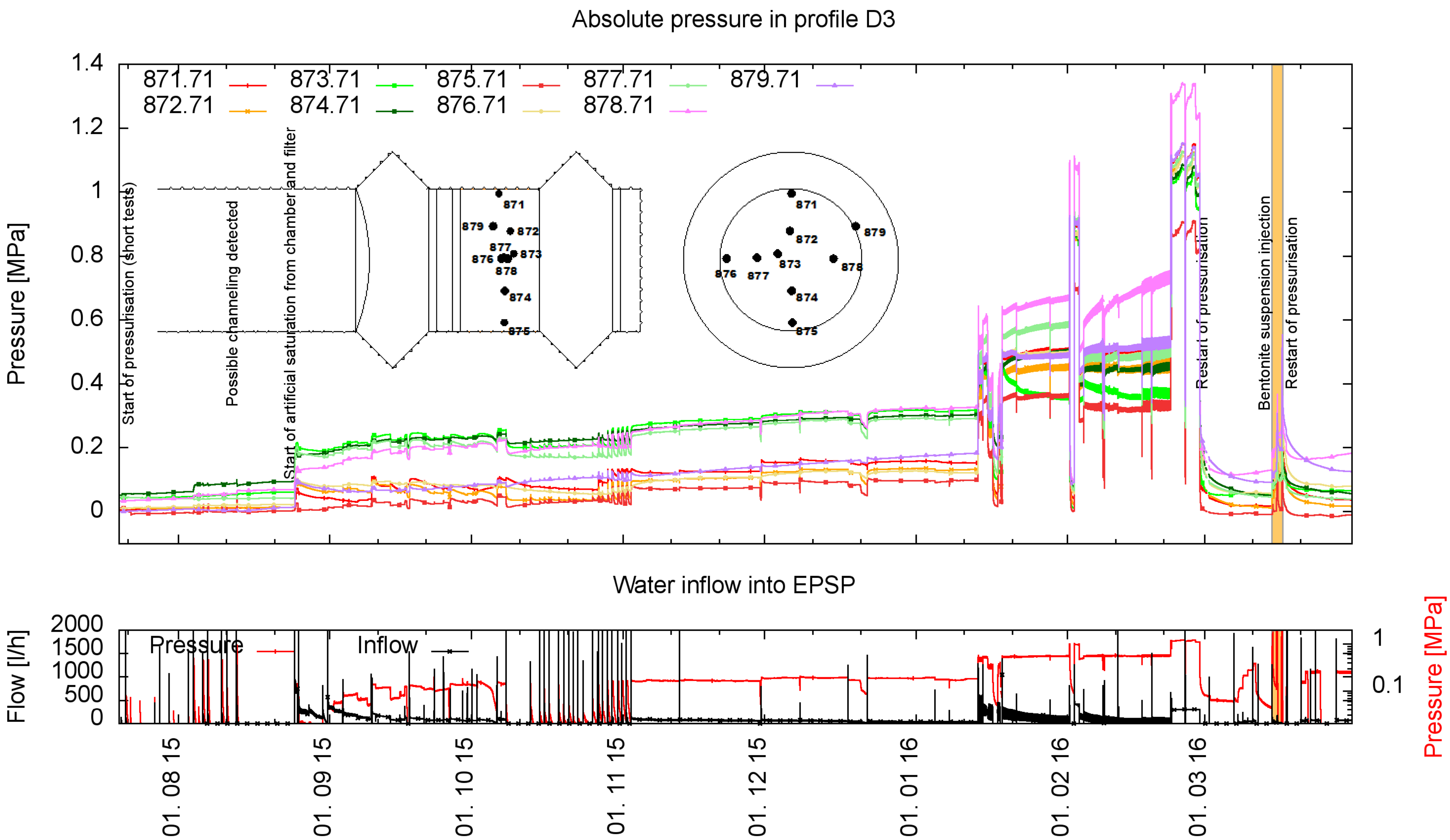



**Figure 5.7:** Total pressure and water flow in the bentonite seal in response to pressurisation of the EPSP experiment.

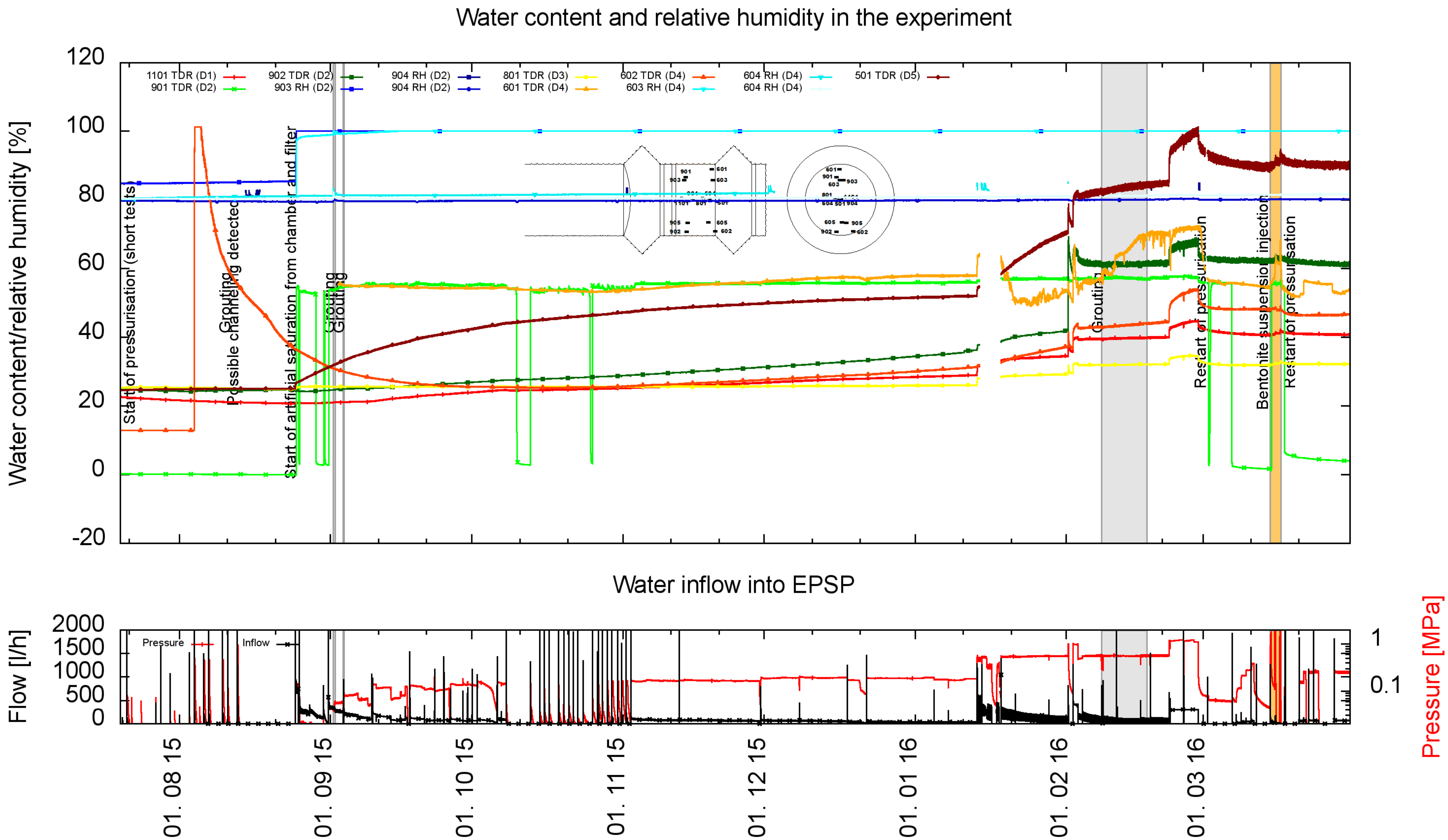



**Figure 5.8:** Water content in the bentonite seal during pressurisation of the EPSP experiment.

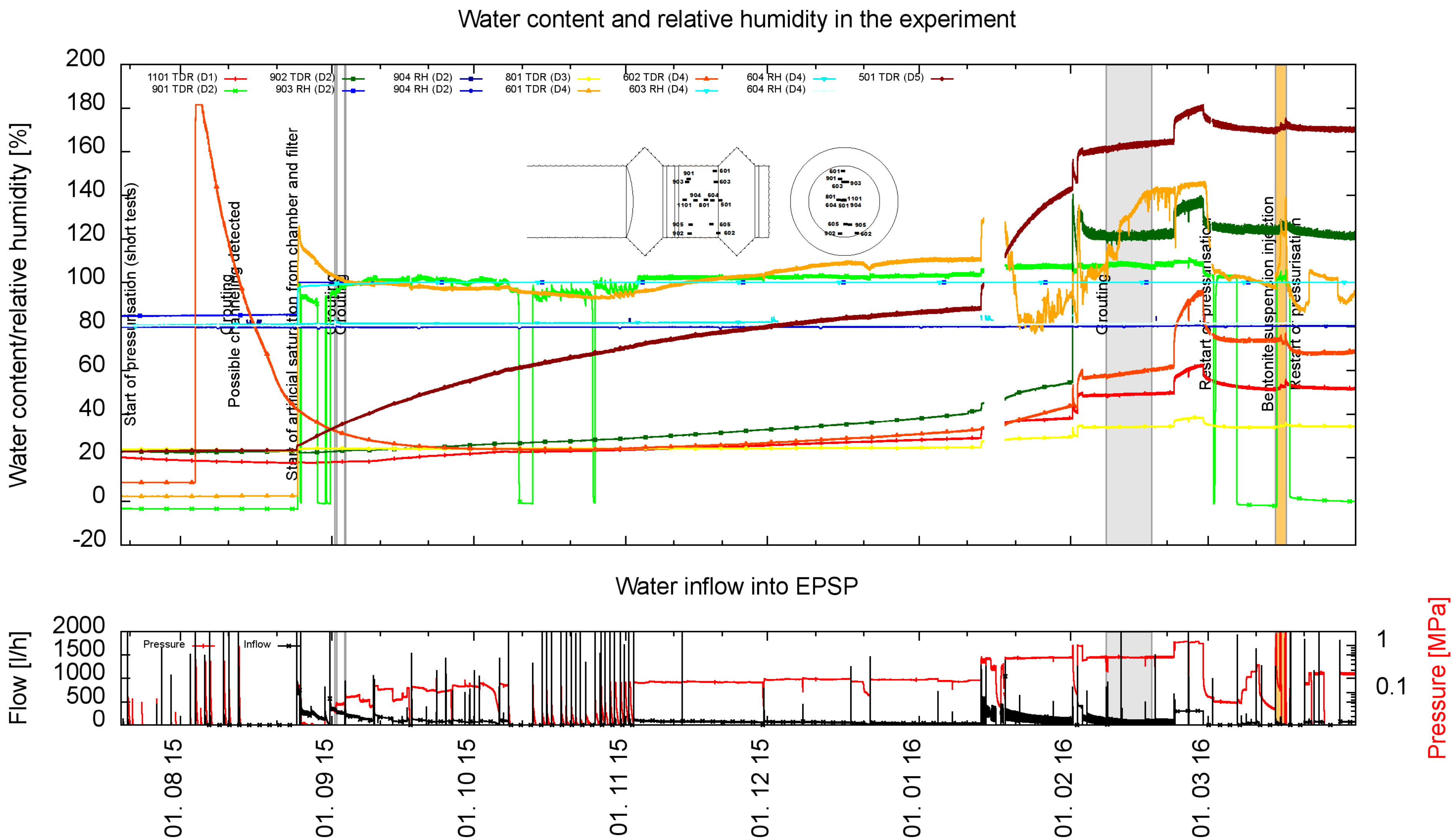



**Figure 5.9:** Water content in during pressurisation of the EPSP experiment.

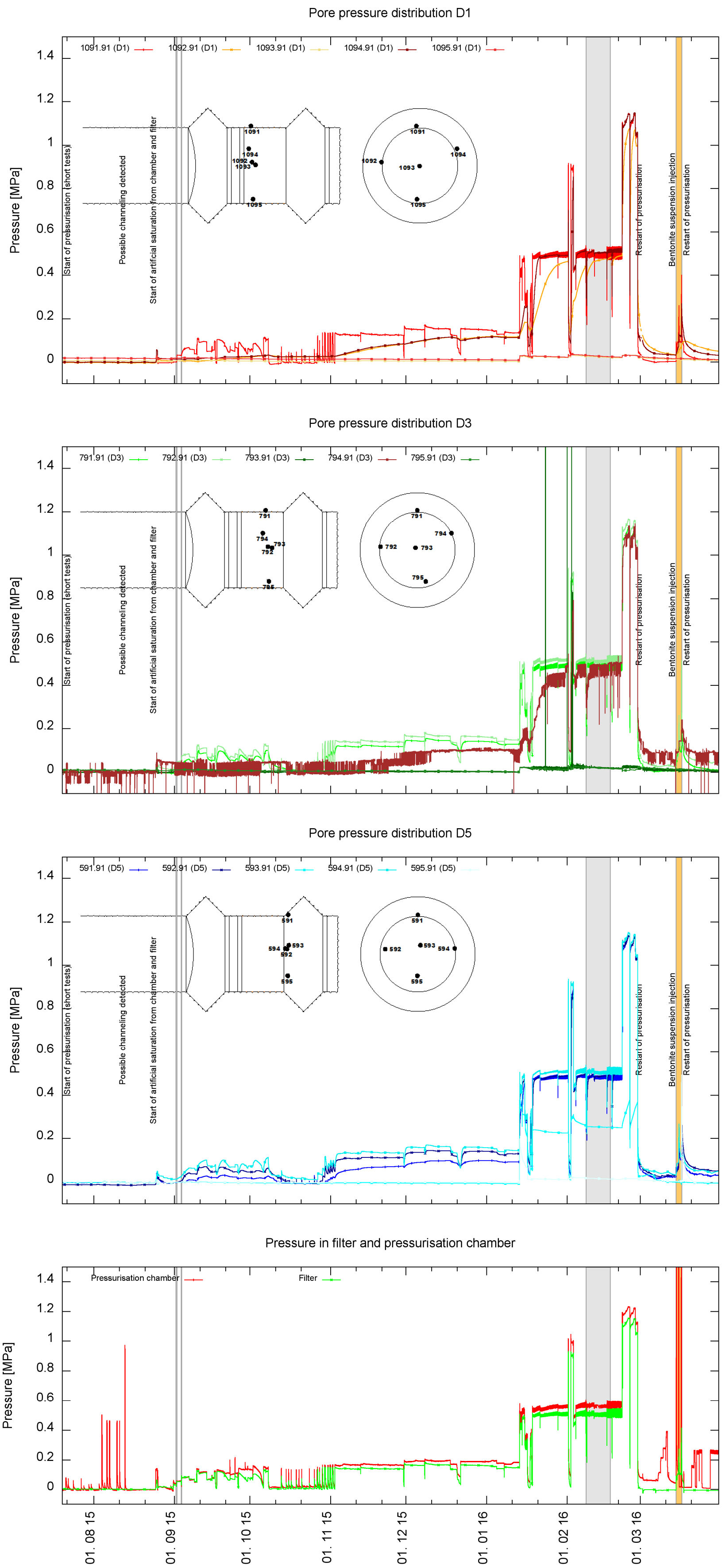



**Figure 5.10:** Pore pressure development in the bentonite seal during the initial pressurisation of the EPSP experiment.

### 5.6 Evaluation of the EPSP Monitoring Systems

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.

During the pilot test and subsequent pressurisation, the instrumentation performed well too. It was possible to reliably track the performance of the experiment, especially in the sealing section.

A key strategy adopted in the monitoring system design was to route cabling perpendicular to the experiment axis. This helped to reduce the negative influence of possible flow along cables.

There have been some problems with water leakage into sensors during the high pressure tests (one of the sensors caused back flooding of several others). The leak has been resealed and the affected sensors disconnected. Fortunately, the sensors affected were temperature sensors which had already fulfilled their primary purpose (monitoring of the temperature evolution of the concrete during curing). Therefore, the impact on the system was minimal. Compartmentalisation and redundancy built into the system helped greatly to reduce the impact of the incident.

The influence of the monitoring system on the installation of the experiment was mostly negative (but manageable). The fixed cabling creates obstacles for the sprayed concrete. This could lead to the creation of “shadows”. Creation of shadows can be mitigated to a large extent by good operation of the shotcrete nozzle by the operator. However, places around such objects are known to be usual weak spots. On the other hand, the protective steel tubing around the monitoring system cables acts as some sort of reinforcement of the plug (although very minor).

A parameter-by-parameter evaluation of the monitoring system, is provided in Table 5.2. The monitoring system is described in more detail in DOPAS (2016b) and Svoboda *et al.* (2016a), and further details on the performance of the EPSP system are provided in Svoboda *et al.* (2016a).

**Table 5.2**: Evaluation of the EPSP experiment monitoring system. Further information is available in Svoboda *et al.* (2016a).

| Sensor | Parameter(s) | Evaluation |
|---|---|---|
| GeoKon 4500SHX-10MPa | Water pressure and pore pressure | The sensors were able track the changes in pore pressure and pressure inside pressurisation chamber and filter.<br><br>There has been slight offset detected between several sensors measuring same place (probably zero measurement difference). |
| GeoKon 4810X-10MPa | Total pressure, pressure between the plug and rock, pressure between the inner plug and separation wall. | The sensors were able to track the development of total pressure in the bentonite section and also in contact between the plug and rock.<br><br>There have been problems during installation where the end cup of the sensor body was easily detachable (just O ring seal holding the cup). Detached cup is one of the possible reasons of leak into sensor system experienced. |

| Sensor | Parameter(s) | Evaluation |
|---|---|---|
| GeoKon 4200A-2 | Strain in the concrete plugs | The sensors were able to track the deformation/strain development in the plugs. The sensors were able to withstand shotcreting (none was damaged). |
| GeoKon 4911-4X | Strain in the rock | The instrumented rock bars were able to track some changes in the rock. However, the reaction of rock was very minimal. |
| LM35DZ (analogue sensor)<br>DS18B20 (digital sensor with 1wire bus) | The temperature development in plugs | The sensors were able to track the temperature development.<br>The advantage and disadvantage of digital DS18B20 is a possibility to use a common cable (bus) for several sensors. This reduces the number of cables needed, but any problem on the cable disables all sensors (the system is less robust). When an electric problem occurs on the bus, the sensors sometimes report wrong value (this is easily detectable). |
| Thermistors or other integrated temperature sensors in other type of sensors | Temperature in the experiment (all parts) | The sensors were able to track the temperature development. These sensors were primarily used for sensors temperature correction and secondarily for temperature monitoring of the experiment.<br>There have been sometimes (rare) problems with GeoKon sensors giving spikes. |
| E+E EE071 | Relative humidity in the bentonite seal | The EE071 were able to track relative humidity changes in the bentonite. It coped very well with flooding of sensors and recovery from it. |
| DECAGON 5TE | Water content in the bentonite seal | The 5TE TDR sensors were able to track development of water content by measurement of dielectric permittivity (and electrical conductivity).<br>The sensors worked well, however there have been problems with calibration for the real plug. The use of pellets makes surrounding of sensor inhomogeneous (pellet size is quite big in comparison to sensor) and this leads to a significant uncertainty in the absolute values of water content from permittivity. |

| Sensor | Parameter(s) | Evaluation |
|---|---|---|
| Siemens SITRANS F M MAG5000/6000 | Inflow into plug | The flow meter has been able track the flow into plug. There have been some problems with very high flows (over specification of flow meter) where flow meter was able to measure the flow however the analogue output into measurement system got saturated. |

## 5.7 Assessment of Compliance with the Design Basis and Evaluation of the Results with Respect to the Experiment Objectives

In this section we discuss the results from the EPSP experiment with reference to:

- Compliance with the design specifications listed in Table 5.1 is discussed in Section 5.7.1.
- The outcomes of the experiment with respect to the objectives presented in Section 5.2.1 are discussed in Section 5.7.2.

Unlike discussion of the FSS experiment, the DOMPLU experiment and the POPLU experiment, compliance with the plug safety functions is not discussed, as the EPSP experiment is focused on materials and expertise development, rather than development of a reference repository plug/seal design.

### 5.7.1 Compliance with Design Specifications on the EPSP Experiment

An evaluation of the compliance of the EPSP experiment with the design specifications presented in Table 5.1 is presented in Table 5.3. The implications are discussed in 5.7.2.

**Table 5.3**: Compliance assessment for key design specifications on the EPSP experiment. The feedback to the design basis is discussed further in the text.

| ID | Requirement / Design Specification | Compliance Assessment | Feedback to Design Basis |
|---|---|---|---|
| EPSPDS01 | The compressive strength of the concrete shall be a minimum of 30 MPa, with a target strength of 40 MPa. | Compliance with the compressive strength requirement was met through testing of the selected concrete mix (see Section 5.2.2). Compliance testing was undertaken according to the Eurocode (static analysis) requirements on concrete strength<br><br>In addition, a sample of the emplaced concrete has been taken and will be tested for compressive strength (and other properties) by an accredited laboratory. Results of this testing are not yet available. | The experience from the EPSP experiment has given confidence that glass-fibre-reinforced low-pH concrete plugs of sufficient strength can be constructed with technology available to the Czech programme, and that such plugs can be incorporated in future tunnel plug designs.<br><br>However, the plug designs for the repository have to be developed, and requirements on the concrete updated for these designs and for the ground conditions where the plugs will be emplaced. This will include the development of a quality control programme to be implemented during repository operation.<br><br>In addition, the suitability of the concrete mix in terms of its chemical performance needs further consideration (see EPSPDS02), and any change in the concrete mix to address the chemical performance will also need to consider the impact on mechanical performance. |
| EPSPDS02 | The pH of the concrete leachate shall be less than 11.7. | Compliance with the pH requirement was met through testing of the selected concrete mix (see Section 5.2.2). | The experience from the EPSP experiment has given confidence that glass-fibre-reinforced low-pH concrete plugs can be constructed with technology available to the Czech programme, and that such plugs can be incorporated in future tunnel plug designs. However, the current requirement adopted for the pH of the concrete leachate in the EPSP experiment specifies a higher pH than typically adopted for low-pH concrete (11.7 compared to 11.0 as adopted in other DOPAS Project experiments and, for example, in the EC ESDRED Project (García-Siñeriz *et al*., 2008). Therefore, the suitability of this requirement, and the shotcrete mix developed to meet it, need review during the on-going programme. |

| ID | Requirement / Design Specification | Compliance Assessment | Feedback to Design Basis |
|---|---|---|---|
| EPSPDS03 | The hydraulic conductivity of the concrete shall be less than 1 x $10^{-10}$ m/s. | Compliance demonstrated through sampling of test specimens prepared in parallel with EPSP installation process. Test samples had a permeability of $7.9\times10^{-11}$ m/s with an uncertainty margin of 2.7%. | This requirement appears appropriate to maintain within the design basis. |
| EPSPDS04 | The temperature of the concrete during curing shall be less than 60°C. | 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 EPSPDS01 and EPSPDS02. |
| EPSPDS05 | The emplaced bentonite shall achieve a density of 1,400 kg/m$^3$. | Based on a mass balance approach, the bentonite dry density is 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. However, as for the other requirements, the designs and quality control programme for the repository requires development at the appropriate time in Czech programme. |

### 5.7.2 Outcomes of the Experiment with Respect to the Objectives

The objectives of the experiment were presented in Section 6.2.1. The outcomes of the experiment with respect to these objectives are discussed in this sub-section.

*Test materials and technology*

There have been significant positive achievements from the overall EPSP experiment concerning materials understanding and technology for installation of tunnel plugs. The following conclusions can be made:

- Czech bentonite B75 is a suitable material for the use as a plug and seal based on structural analyses performed, and geotechnical parameters such as swelling pressure, plasticity, etc. (see Vašíček *et al.*, 2014). The B75 bentonite was tested before and during the EPSP experiment, and it is suitable to be made into pellets, and can be compacted to the required density. B75 can also be used for spraying.
- The EPSP plug design is suitable for use as a tunnel plug. Modifications to the plug shape may be necessary in other places in the repository. Plugs can be used as a

separation of extensive fracture zones, or for closure of filled parts of the repository. Detailed designs of all of the plugs will be added to the Czech conceptual design at the appropriate stage in the programme.

- Glass-fibre-reinforced low-pH shotcrete can be used for the construction of the inner and outer plugs. The material used in the EPSP experiment had limited crack formation and provided stability and pressure resistance to the overall plug structure.
- The experience with the shotclay technology is of interest and relevance to the design of plugs and seals by all WMOs, and could be further tested and developed.

*Extend laboratory experience to the underground environment and to full scale*

- In the repository, the plug location has to be carefully selected with respect to the geological structure, especially the presence of any fractures that may compromise the plug function. Detailed description of the rock mass in the plug location is necessary.
- Contact grouting will be needed for the sealing of the contact zones between the plug and the rock mass.
- The time of the construction of plugs must be optimised with respect to the time schedule of the works in the repository. The period over which plugs are constructed must be reduced, and plug construction must not disturb the normal operations in the repository.

*Build the knowledge and practical expertise of the SÚRAO personnel and other partners*

- During the DOPAS Project, and the EPSP experiment in particular, SÚRAO staff benefitted from first-hand experience of design and testing of repository systems, especially design of plug systems. The expertise gained through this experience will be utilised during the upcoming repository design work planned in the Czech Republic. In particular, it will enable a revised plug specification to be used as the basis for the revision of the repository reference project.
- Practical knowledge regarding technologies and materials has been gained with respect to the suitability of the tested materials for application in the repository.
- A network of specialists from different organisations has been established during the EPSP experiment, and this network will be exploited in future repository design work.

*Provide an important test-bed in developing a final plug design and procedure for implementation*

- The reference repository design in the Czech national programme reference project (Pospíšková, 2012) incorporated a simple concept for tunnel plugs. The knowledge gained within the EPSP experiment and the DOPAS Project in general will allow more detailed designs for tunnel plugs to be developed in the future.
- The material, technologies and logistics that have been tested within the DOPAS Project, and the practical experience gained, will be used in development of the Czech repository.
- In the EPSP experiment, a multi-layer plug has been successfully designed, constructed and tested.

*Contribute towards the development of a reference design for tunnel plugs*

- A more advanced (and detailed) reference design will be produced based on results of the DOPAS Project. This will be based on the multi-layer EPSP plug performance, on learning gained by SÚRAO and its contractors during construction of the plug, such as the importance of logistics on repository operation and will take account of the scale of plugs required in the repository.
- The results serve as input into repository design optimisation.

*Develop indications on crystalline host rock requirements*

- The experience from the EPSP experiment demonstrate that there is a clear need to limit the number of faults, open fractures and other brittle structures in tunnel and tunnel plug locations.
- It is necessary to have a description of mineralogical assemblages as part of the characterisation of rock structures to predict secondary dissolution processes.
- Extensive knowledge of underground water flow is necessary; groundwater flow has to be limited for successful plugging of tunnels.

*Support the site selection programme*

- The experience from the EPSP experiment has demonstrated that the site selection process must deliver a rock with suitable mechanical and hydraulic properties, and further analysis of the experiment results can provide some constraints on these properties.
- The quality of the rock mass at plug locations is extremely important for the performance of the plug. Therefore, site selection criteria should include evidence that suitable plug locations, with respect to rock quality and groundwater flow, are likely to be identified during detailed site investigation work.

## 5.8 Conclusions from the 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. 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. This will include further development of plug designs tailored to the overall disposal concept and the site conditions.

# 6 SKB's Deposition Tunnel Plug

This chapter discusses the achievements in the DOPAS Project, in particular the design, construction and pressurisation of the DOMPLU experiment, with respect to SKB's reference deposition tunnel plug:

- In Section 6.1, the design basis for the reference deposition tunnel plug is described, focusing on the safety functions assigned to the plug, a summary of the reference design, and presentation of the key design specifications contained within the design basis and which are directly tested through measurement of the results of the DOMPLU experiment. More information on the design basis can be found in White *et al.* (2014).
- In Section 6.2, the DOMPLU experiment is described, including the objectives of the experiment, and a summary of the design work (including the supporting numerical modelling), construction of the experiment niche and installation of the DOMPLU components. More details on the construction of the DOMPLU experiment are in DOPAS (2016b).
- Section 6.3 discusses the learning from the DOMPLU experiment with respect to the operational issues that will be faced during installation of SKB's reference deposition tunnel plug.
- In Section 6.4, the performance prior to pressurisation of the DOMPLU components is evaluated, and conclusions drawn regarding the suitability of the materials and the emplacement methods used to install the materials for application in the repository.
- In Section 6.5, the performance during pressurisation of the DOMPLU components is evaluated, and conclusions drawn regarding the suitability of the materials to provide the necessary performance in a repository.
- Section 6.6 evaluates the performance of the monitoring system used in the DOMPLU experiment and its applicability in repository monitoring.
- Section 6.7 presents an evaluation of the compliance of the DOMPLU experiment with the design basis, the feedback of the results to the design basis and discusses the learning outcomes from the work.
- Section 6.8 presents the overall conclusions from the DOMPLU experiment relating to SKB's reference deposition tunnel plug.

The information presented in this chapter focuses on a summary of the performance of the experiment. In addition to the further information on the design basis and construction of the DOMPLU experiment provided in other reports and references therein as indicated above, further details on the DOMPLU experiment are provided in the DOMPLU experiment summary report (Grahm *et al.*, 2016).

Modelling of the long-term behaviour of the reference deposition tunnel plug was not part of the DOPAS Project.

## 6.1 SKB Deposition Tunnel Plug Design Basis

### 6.1.1 Deposition Tunnel Plug Safety Functions

The KBS-3V method is proposed by SKB in their application for a construction licence for the disposal of spent fuel packaged in copper canisters with cast iron inserts in a crystalline host rock (SKB, 2011). 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 6.1).

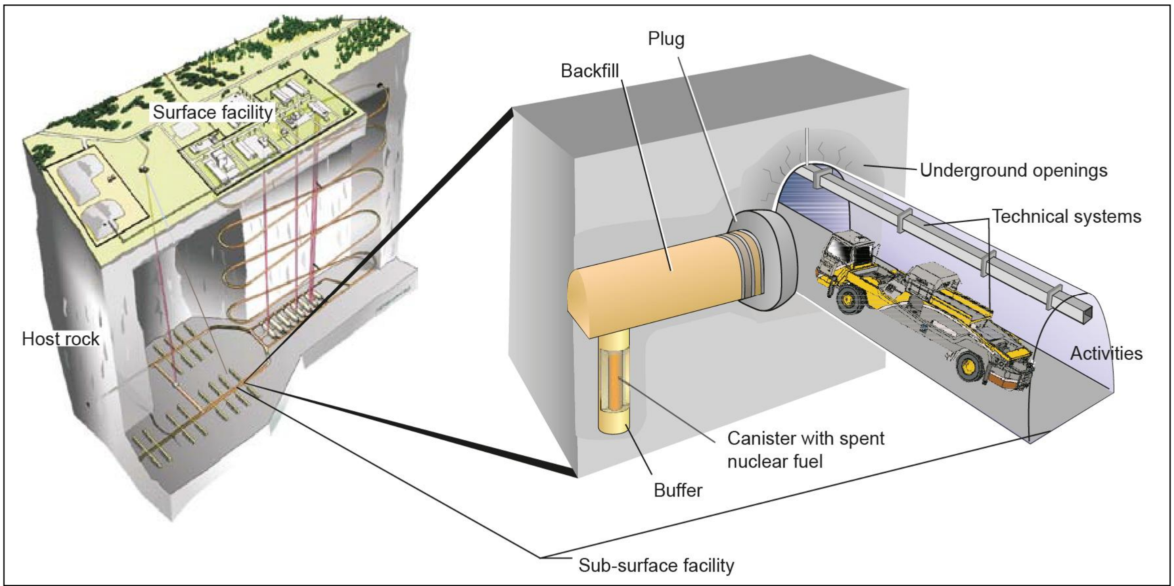



**Figure 6.1**: The KBS-3V repository and the location of the deposition tunnel plug (SKB, 2010a).

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[6]:

- 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[7].

---

[6] 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. This is discussed further in Section 6.7.

[7] 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.

### 6.1.2 Deposition Tunnel Plug Design

The current SKB reference conceptual design for a deposition tunnel plug is described in SKB's design, production and initial state of the backfill and plug in deposition tunnels report (SKB, 2010b), and includes the following components (see Figure 6.2) (see further discussion in White and Doudou, 2014):

- Concrete Plug: The reference concrete plug is a dome-shaped structure made of low-pH reinforced concrete. The term "low-pH concrete" is used by SKB to refer to concrete generating leachate with a pH of less than 11. 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.

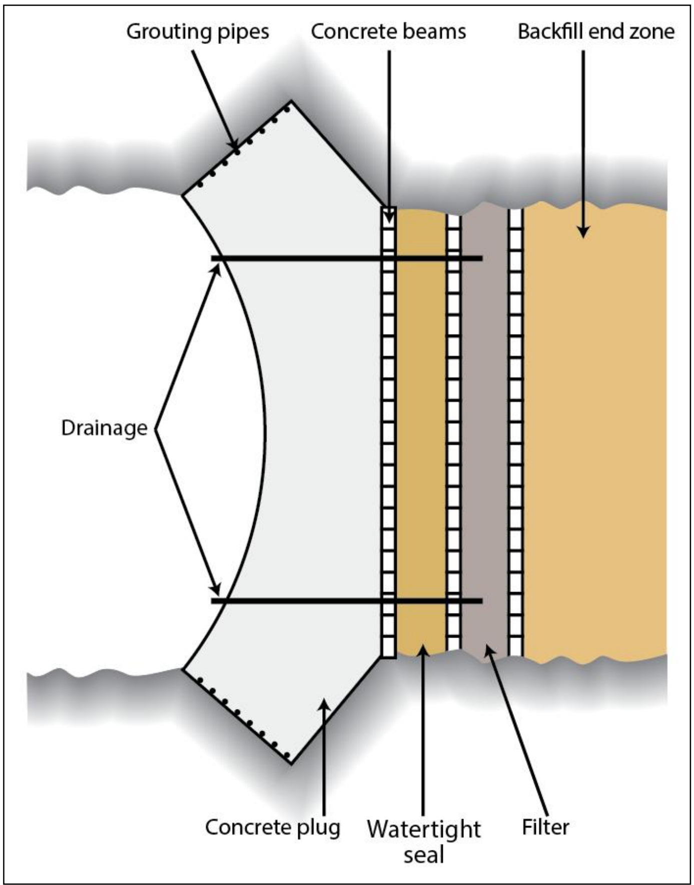



**Figure 6.2:** Schematic illustration of the deposition tunnel plug components in SKB's reference conceptual design (SKB, 2010b). There are three concrete beams in the conceptual design; these are sometimes referred to as the inner, middle and outer concrete beams or delimiters, with the inner concrete beam being adjacent to the backfill end zone.

- Watertight Seal: The watertight seal is made of bentonite blocks and pellets in a similar configuration to the backfill. The functions of the watertight seal are:
  - To seal water leakage paths through small cracks in the concrete plug or between the concrete and the rock surface.

- To reduce the water pressure acting on the concrete dome so that no unfavourable water pressure is applied in the interface between the rock and the concrete, and so that the water pressure within the backfilled deposition tunnel is equalised.

- Backfill End Zone: The part of the backfill closest to the plug in which the density is reduced to manage the swelling pressure loads on the plug.
- Filter: The filter is made of sand or gravel. Its function is to collect groundwater leaking from the backfilled deposition tunnel and, if required, drain it to the drainage pipes, so that no water pressure is applied on the concrete plug before it has cured and gained full strength. The filter will also facilitate saturation of the bentonite seal.
- Concrete beams (Delimiters): The beams are made of low-pH reinforced concrete. Their function is to facilitate the construction works. The outer beams (towards the concrete plug) are covered with a thin layer of shotcrete to prevent the concrete slurry from mixing with the bentonite during casting of the concrete plug. The function of the outer beams is to keep the watertight seal in place during installation, i.e., acting as an inner formwork for the concrete dome. The inner beams (towards the deposition tunnel) shall keep the backfill in place during installation. The middle beams shall keep the filter in place during installation and are designed to withstand the development of the pressure during swelling of the watertight seal and/or backfill.
- Drainage pipes: The drainage pipes need to function throughout the operational period (up to 100 years), and are made of steel or titanium. They are required to drain the water collected in the filter and transport it out of the deposition tunnel, which will prevent water pressure being applied on the concrete plug before it has cured and gained full strength.
- Grouting pipes: The grouting pipes are made of steel and may be isolated by geotextile to prevent blocking during pouring. They shall be grouted when the concrete has reached a certain level of strength and shrinkage. The grout shall tighten the contact area between the concrete plug and rock and contribute to keeping the concrete plug under compression.

#### 6.1.3 Key Design Specifications in the DOMPLU Experiment Design Basis

The key design specifications contained within the design basis and which are directly tested through measurement of the results of the DOMPLU experiment or during materials development are presented in Table 6.1. More information on the design basis can be found in White *et al.* (2014). The full design basis contains a much greater number of requirements; only the most significant design specifications have been listed here and are considered in this summary report (see Section 3.5 for context and justification for the selection of “key” design specifications). Evaluation of the performance of the DOMPLU experiment compared to the design basis is an on-going activity within SKB.

**Table 6.1:** Key design specifications tested through measurement of the results of the DOMPLU experiment or during materials development as part of the experiment.

| ID | Design Specification | Justification for Adopting the Design Specification | Compliance Approach Applied in Experiment |
|---|---|---|---|
| DOMDS01 | The backfill transition zone shall reduce the swelling pressure coming from the backfill in accordance with the swelling pressure acting on the concrete dome being a maximum of 2 MPa. | The purpose of this requirement is to define and calculate a safety class for the concrete structure of the deposition tunnel plug. | A design prerequisite for the DOMPLU experiment was to dimension the bentonite swelling pressure to be about 2 MPa. Compliance was tested by measurement of pressures and displacements throughout the plug and comparison with the numerical models used to dimension the experiment. |
| DOMDS02 | The delimiter separating the backfill and filter shall be open for drainage/saturation water to pass in both directions. | Keeping the delimiter open for drainage/saturation water to pass in both directions allows groundwater drainage to enter the filter and subsequently ensures an even distribution of water over the entire cross section of the backfill transition zone. | Measurements of relative humidity and pore pressure on each side of the delimiter.<br>The filter function of the LECA® beams should also be demonstrated by laboratory experiments before installation. |
| DOMDS03 | The delimiter separating the backfill and filter shall be capable of displacement in response to swelling of the seal and backfill. | Axial movements will occur from the swelling pressure of the bentonite seal and the backfill respectively. | In the DOMPLU experiment, displacement was checked through emplacement of displacement sensors. |
| DOMDS04 | The delimiter separating the gravel filter and the bentonite seal must allow water from the filter to flow through it, evenly distributed over its entire cross-section. | Keeping the delimiter open for drainage/saturation water to pass into the bentonite seal allows use of the filter to artificially saturate the bentonite seal by an even distribution of water over its entire cross section. | Measurements of relative humidity and pore pressure on each side of the delimiter.<br>The performance of the delimiter should also be demonstrated by laboratory experiments before installation. |
| DOMDS05 | The delimiter separating the filter and the bentonite seal shall be capable of displacement in response to swelling of the bentonite seal. | Axial movements will occur from the swelling pressure of the bentonite seal and the backfill respectively. | In the DOMPLU experiment, displacement was checked through emplacement of displacement sensors. |

| ID | Design Specification | Justification for Adopting the Design Specification | Compliance Approach Applied in Experiment |
|---|---|---|---|
| DOMDS06 | 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 1,700 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).<br>Comparison of measured and calculated values will help to underpin the compliance approach to be applied in the repository. |
| DOMDS07 | 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. Potential reactions include the loss of swelling capacity, and changes in porosity, mineralogical composition, or sorption capacity. To minimise these reactions, low-pH concrete must be used. | Statement in construction report providing evidence that B200 mix has been used. Evidence that the leachate from this concrete will be of low pH is provided in Vogt *et al.* (2009). |
| DOMDS08 | The concrete shall have a compressive strength of 54 MPa (at age of 90 days), maturity conditions according to Swedish standard regulations. | The concrete dome must resist deformation and confine the backfill, and, in order to do this must resist the applied stresses. 54 MPa was the compressive strength measured for the B200 concrete during material development and testing (Vogt *et al.*, 2009). This value was subsequently used in the detailed design of the concrete plug, and the plug design is therefore based on a compressive strength of 54 MPa (Malm, 2012). As such, a compressive strength of 54 MPa has been adopted as a design specification for the DOMPLU experiment. | Laboratory testing of B200 concrete, including comparison with previous test results, published in Vogt *et al.* (2009). |

| ID | Design Specification | Justification for Adopting the Design Specification | Compliance Approach Applied in Experiment |
|---|---|---|---|
| DOMDS09 | The concrete dome shall be cast without reinforcement and therefore the temperature in the concrete dome shall not exceed 20°C during curing. | A low temperature, compared to the other experiments, is used owing to the non-reinforcement concrete dome and the unique application of a cooling system to reduce the impact of hydration heat on the concrete temperature, to facilitate release of the concrete dome from the host rock in order to allow a wider space for contact grouting, and to pre-stress the concrete dome prior to contact grouting (see further discussion in Section 9.2.2). | 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 (for example, by arguing that the numerical models have been calibrated during the DOMPLU experiment). |
| DOMDS10 | A sequential cooling process shall be performed to contract the concrete dome prior to and during contact grouting. | An extended gap between the concrete and rock (release of the concrete from the rock) is required for successful concrete grouting. | Joint meters to monitor the development of the gap.<br>Strain sensors to monitor the pre-stress in the concrete dome after cooling. |
| DOMDS11 | The full pressure against the concrete dome must not appear until it has cured and gained sufficient strength. | If pressure is applied before the dome has gained sufficient strength it could fail. | Understanding of the behaviour of concrete during material testing, monitoring of the pressure of the formwork during concrete pouring, monitoring of water pressure in the filter and monitoring of total pressure within the bentonite seal. |
| DOMDS12 | The plug shall resist the sum of the hydrostatic pressure at repository depth and the swelling pressure of the backfill until the main tunnel is filled; 5 MPa water pressure and the swelling pressure from the backfill in the section adjacent to the plug. Currently, the backfill swelling pressure is assumed to be 2 MPa with the help of backfill transition zone that decreases the load from a high load to 2 MPa. | A requirement of 5 MPa gives a safety margin to a worst-case groundwater pressure during operations in the Spent Fuel Repository in Forsmark, located -470 m below sea level, based on the hydrostatic pressure that could exist after saturation of the repository.<br>2 MPa is a value derived from modelling of the reference deposition tunnel plug system, and includes the swelling pressures developed in the backfill transition zone and the bentonite seal, and the related displacement of the filter during operation of the plug. | This is a principal objective of the DOMPLU test, i.e. construct the concrete dome and demonstrate that it can be pressurised. Therefore, the compliance approach was to conduct the full-scale test. |

| ID | Design Specification | Justification for Adopting the Design Specification | Compliance Approach Applied in Experiment |
|---|---|---|---|
| DOMDS13 | 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.<br>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.<br>Recent calculations predicted a leakage of 0.1 l/min. 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.<br>Random checks of bentonite content in the water during drainage from the filter. |
| DOMDS14 | Provide a barrier against air and vapour transports, to and from the deposition tunnel. | This requirement was identified during course of the project. Hence, an addition to the licence application has been submitted by SKB to the Swedish Radiation Safety Authority. | A saturated bentonite seal will ensure gas tightness of the plug system, and, therefore, the compliance approach is to monitor the relative humidity of the bentonite seal. |

Notes:
1. Requirement DOMDS06 would be written as two requirements in a formal requirements management system, but, for clarity of presentation and discussion, has been written as a single requirement in this report.

## 6.2 Summary of DOMPLU Experiment

### 6.2.1 Objectives of DOMPLU

The DOMPLU experiment was a full-scale test of the reference deposition tunnel plug in SKB's repository design. The DOMPLU design consisted 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 6.3) (Grahm *et al*., 2015).

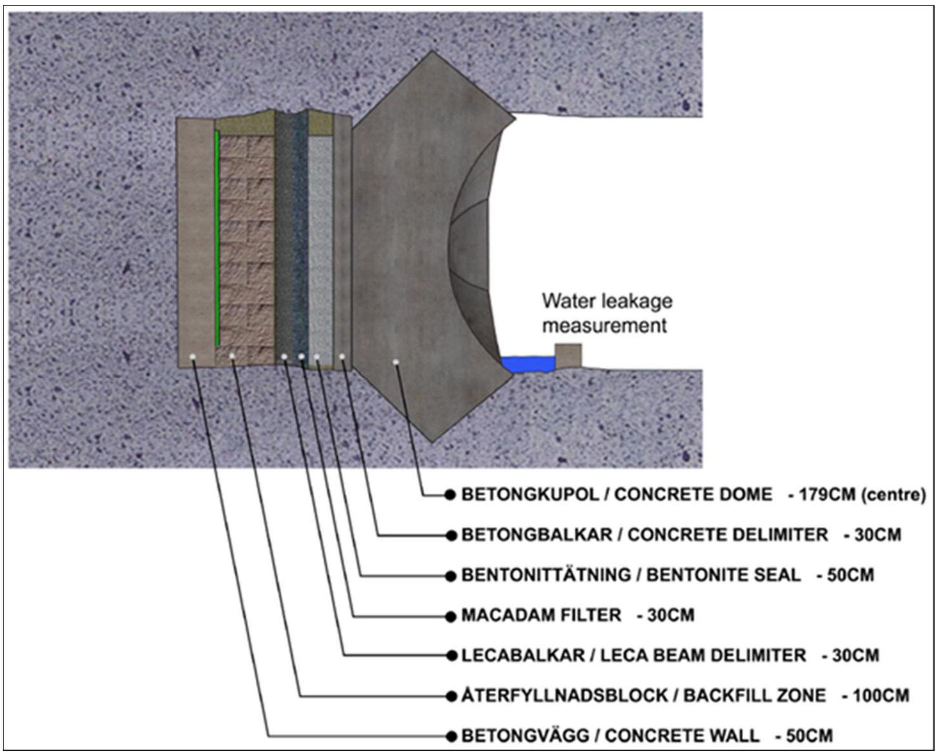



**Figure 6.3**: Schematic illustration of the DOMPLU experiment design (Grahm *et al.*, 2015).

The DOMPLU experiment is part of an on-going SKB testing and demonstration programme (SKB, 2013). The overall objective of the test is to reduce uncertainties in the long-term 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 (see further discussion in White and Doudou, 2014 and Grahm *et al*., 2015):

- To finalise the details of the reference design.
- To demonstrate the feasibility of plug installation.
- To validate 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.

- 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 (<0.1 l/min as discussed by Grahm *et al.*, 2015).
- To improve testing and quality control during repository construction.

In order to meet these objectives, the DOMPLU design included specific design modifications compared to the reference design. These modifications were introduced to test if they could be adopted in the reference design in the future (White and Doudou, 2014 and Grahm *et al*., 2015):

- 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, LECA® beams and gravel with a high hydraulic conductivity are used. The filter thickness is 600 mm, made up of 300 mm of gravel (with a particle size of 2-4 mm) and 300 mm of LECA® beams, compared to a thickness of 700 mm, which is specified in the reference design for the filter.
- The middle delimiter between the filter and the 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 as for 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 avoid potential cracking of the concrete dome during shrinkage.
- Cooling pipes are 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 are 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 been tested by SKB before.
- 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.

### 6.2.2 Summary of DOMPLU Design and Construction

The design and construction of DOMPLU included the following activities:

- Materials development and testing of the proposed concrete mix for the low-pH SCC concrete dome, the bentonite seal, the filter and the delimiters.
- Structural design work to decide the geometrical properties of the experiment and to design the pressurisation system.
- Siting and excavation of the 14-m long DOMPLU experiment niche at the Äspö Hard Rock Laboratory, 450 m below ground in crystalline rock.
- Installation of the DOMPLU experiment components in a replicated KBS-3V reference deposition tunnel. Installation of sensors in backfill, filter, bentonite seal and concrete dome was done in conjunction with the installation of each component.
- A water pressurisation system and leakage monitoring system were also installed.

The first three parts of this work (materials development and testing, structural design work, and siting and excavation of the DOMPLU experiment niche) were undertaken by SKB and Posiva outside the scope of the DOPAS Project. The work is reported in more detail in Grahm *et al*. (2015). They are discussed here in order to provide an overall discussion of the experiment, consistent with the report objectives and consistent with the description of other experiments in this report.

***Materials Development and Testing: Including Compliance with DOMDS09 & DOMDS10***

A concrete mix for a low-pH self-compacting concrete (SCC), denoted B200, has previously been developed specifically for use in the deposition tunnel plugs of SKB's repository (Vogt *et al.*, 2009). The approach to making the B200 low-pH SCC was adopted from basic understanding of concrete mixes, i.e. by composing the binder of at least 35 to 40 wt. % silica fume which is an active pozzolana that reacts with Portland cement in such a way that it changes the chemical properties of the cement paste and ensures that the pH of leachate waters is less than 11 (thereby meeting design specification DOMDS07). Testing of this concrete was required as part of the DOPAS Project to ensure that it provided the necessary strength (DOMDS08), shrinkage, creep and binding properties to the host rock, given the ambition to demonstrate that the concrete could be emplaced without reinforcement (e.g. Figure 6.4) (Grahm *et al*., 2015). Testing confirmed that B200 was suitable for use as the mix for the construction of the concrete dome without reinforcement. However, experiences from the B200 concrete test series showed that further clarification is needed regarding quality control requirements and acceptance criteria of the young concrete properties. Contact grouting was performed with a commercial product *Injektering 30* from Cementa (see Grahm *et al*., 2015). Low-pH grout was not used since the amount of cement for contact grouting is less than 1:20 of the cement content in the concrete dome. The use of Injektering 30 is also proven technology.

Experimental tests were carried out to investigate the properties of the bentonite sealing materials, including compaction properties of the bentonite, strength of the blocks, compressibility, swelling pressure, hydraulic conductivity, and self-sealing of fractures in the rock and slots between the bentonite blocks (Grahm *et al*., 2015; Börgesson *et al*., 2015). The tests allowed the development of a revised specification, which balanced the requirements for dry density, water content and strength. This is necessary to allow the bentonite blocks to be handled using the vacuum lifting tool developed for application in the repository. The testing also provided input data on compression/expansion properties, and swelling pressure and hydraulic conductivity, which were necessary for conducting numerical modelling. The tests confirmed that compressed MX-80 bentonite blocks with 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.

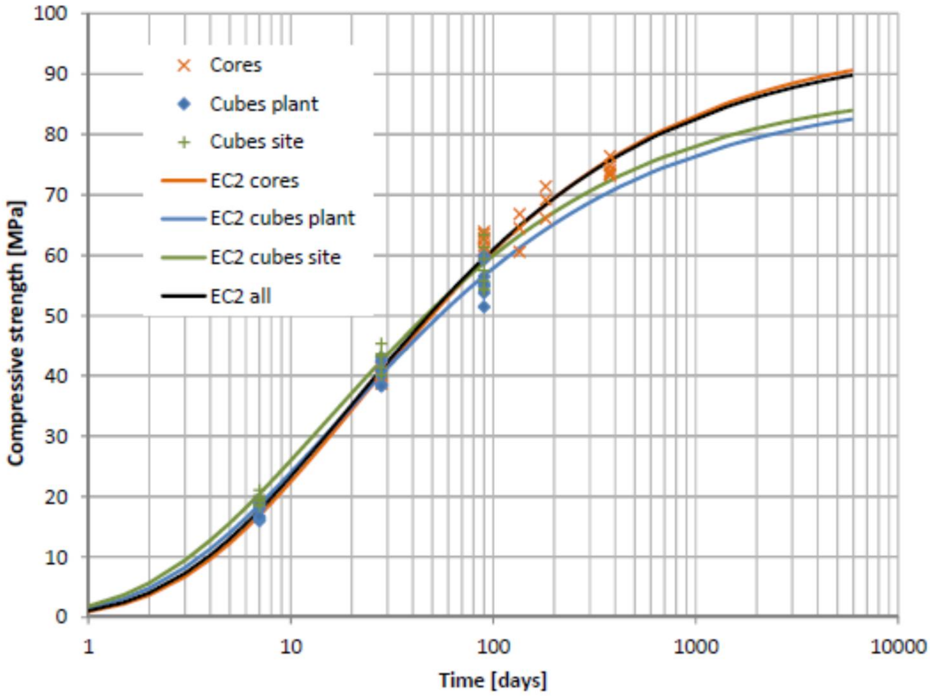



**Figure 6.4**: Development of the compressive strength of B200 concrete with time. Results include tests undertaken at the concrete plant and at the Äspö HRL in connection with the casting of dome plug. Also included are results of testing cores drilled in the monolith. Best fit curves of the strength development according to Eurocode 2 (2008) are also shown. From Magnusson and Mathern (2015).

Materials were tested to select the most appropriate material composition for the filter. The testing identified gravel, with a grain size range between 2-4 mm, as the preferred material for the filter. This material had the highest hydraulic conductivity of the materials tested and its hydraulic conductivity was also only slightly affected by an increased dry density. It also maintains its draining ability when exposed to water flow with high bentonite content.

It was also decided to test geotextile 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.

LECA® was selected as the concrete beam delimiter based on its hydraulic conductivity and also because it maintains it hydraulic performance when exposed to a water flow with high bentonite content (it does not clog). Consequently, the concrete delimiter was replaced by 30-cm-thick LECA® beams between backfill and gravel filter. The LECA® beams were considered to be part of the filter and thus the thickness of the gravel layer could be reduced to 30 cm.

### *Structural Design Work*

The structural design work undertaken for the DOMPLU experiment included use of a scale model test in the laboratory, and analytical and numerical calculations, which are described in full in Börgesson *et al*. (2015) and are summarised in DOPAS (2016b). These two different approaches were mainly used to decide the geometrical properties of the DOMPLU experiment, to simulate the behaviour of the plug system, and to assist with the design of the pressurisation sequence and the water pressure elevation in full-scale testing. An important conclusion from the scale model test was that effective sealing is reached when the swelling pressure exceeds 500 kPa in all parts of the bentonite seal. Calculations acknowledged the swelling pressure development to be a slow process; it would take at least two years to reach 500-1000 kPa in a full-scale seal, and eight years for the bentonite to fully saturate and reach a swelling pressure of 2 MPa.

### *Siting and Excavation of the DOMPLU Experiment Niche*

A requirement was established to install the DOMPLU experiment in the crystalline rock at -450 m below the ground surface, where a groundwater pressure of about 3.2 MPa could be expected. At this depth, conditions would be as close to the final repository as is feasible within the Äspö HRL and would facilitate pressurisation more readily than shallower depths.

A preferred location for the DOMPLU experiment niche at the lowest level of the Äspö HRL was identified, but to be accepted as the location for the experiment, confirmation that the site met the rock requirements was needed. These requirements included:

- No continuous fractures longer than the tunnel diameter in the experiment niche.
- No fractures, longer than 1 m, or water-bearing features at the plug location.
- No fractures with an angle of incidence less than 30º against the tunnel axis in the location of the concrete dome.

The feasibility of the preferred experiment tunnel location was tested against these requirements by drilling a core using a single pilot borehole followed by high-pressure stepwise injection tests in the borehole. The results of the core logging and hydraulic testing indicated that the rock had no fractures of the type specified in the rock requirements. Examination of the borehole indicated that the preferred location was acceptable.

Drill and blast techniques were used to excavate the experiment tunnel. It was decided to attempt to reduce the magnitude of the EDZ through careful blasting in a two-step excavation method. In the two-step method, first, holes in the middle of the tunnel are drilled and blasted before perimeter holes around the tunnel are blasted. The octagonal slot for the concrete dome plug was excavated by use of a wire sawing technique to obtain a smooth surface that should facilitate release of the concrete dome from the rock during early shrinkage and during pre-stressing of the concrete prior to contact grouting (see DOPAS, 2016b and Grahm *et al*., 2015 for further information).

### *Installation of the DOMPLU Experiment Components*

All installed components of the plug system in DOMPLU are illustrated in Figure 6.3. Some components of the experiment were installed separately while others were installed in parallel with assembly of the components progressing vertically. The stages in installation were as follows (installation is described in more detail in DOPAS, 2016b and Grahm *et al*., 2015):

- The concrete back wall.
- The bentonite backfill and LECA® beams inner delimiter.

- The gravel filter, bentonite seal and concrete beams outer delimiter.
- The concrete dome.
- The contact grouting (not shown in Figure 6.3).
- The plastic sheet (not shown in Figure 6.3).
- Installation of the monitoring system.

The monitoring system was installed in parallel with installation of the components (see DOPAS, 2016b and Grahm *et al.*, 2015, for a discussion of the installation of the monitoring system).

The installation of the plug, from installation of the backfill blocks to casting of the concrete dome, and including installation of the monitoring system, took about two months. This period does not include the time required for excavating the tunnel, excavating the slot abutment, casting the concrete back wall, drilling lead-through boreholes and other preparations such as concreting of the remaining boreholes from wire sawing and casting of plinths for the LECA® delimiter and the concrete delimiter. The monitoring system is described in detail in Grahm *et al*. (2015).

## 6.3 Learning Related to Construction and Operational Issues

Evaluation of the use of wire sawing to excavate the slot for the concrete dome was facilitated by laser scanning of the performed cuts (Grahm and Karlzén, 2015). The results of the laser scanning were compared to the theoretical geometry of the slot. The results showed that, in general, the resulting excavation is deeper than the theoretical plane in the centre-bottom of almost every cut. The extent of the deviations was not judged to be significant for the performance of the slot (in eight of the 16 cuts the deviation at the intersection of the two cuts was less ≤2 cm, with deviations in the other cuts ranging from 9-29 cm). However, release of stresses in the rock reduces the deviations from the theoretical shape, and further work on the wire sawing method will investigate methods to do so before the cutting begins (e.g. through drilling of additional boreholes). Further information on the wire sawing is provided in Grahm and Karlzén (2015).

One of the benefits from undertaking the DOMPLU full-scale experiment ahead of repository operations is that the design can be modified, where appropriate, according to the method to be used for installation of the experiment. The bentonite blocks used in the DOMPLU experiment were selected to be 500 x 571 x 300 mm. The height of the blocks (300 mm) was selected to be half the height of the concrete beam delimiters, in order to support parallel emplacement of the two components. The depth of the blocks (500 mm) was based on results of the scaled laboratory models and numerical modelling. One of the recommendations coming from the DOMPLU experiment is that the dimensions of the watertight seal bentonite blocks should correspond to the dimensions of the reference backfill blocks to allow the same production tools to be used (Grahm *et al*., 2015).

It was found that installation of the concrete beams, filter and seal pellets near the tunnel ceiling were quite difficult. Detailed methods and instructions for installation should be produced during detailed design. The worker safety aspect of working at heights, for instance, during installation of cooling pipes where a sky-lift could not easily be used, should also be studied further (Grahm *et al*., 2015).

The formwork was judged by the staff to be both solid and well designed. A modification with a man-hole was suggested by the workers for easier positioning of the larger upper parts.

Possibly the upper part of the formwork could also be re-designed as one piece to facilitate fitting (Grahm *et al*., 2015).

## 6.4 Evaluation of Performance of DOMPLU Components Prior to Pressurisation

In this section the performance at the time of installation of the DOMPLU experiment with respect to the design specifications listed in Table 4.1 is evaluated:

- Section 6.4.1 discusses the monitoring of the pressure on the formwork during concrete pouring, which contributes to the compliance assessment for DOMDS10.
- Section 6.4.2 discusses the monitoring of the temperature in the concrete dome, which contributes to compliance with DOMDS09.
- Section 6.4.3 discusses the release of the concrete dome from the rock, with respect to DOMDS10.

The system used to measure and monitor the installation of DOMPLU is described in DOPAS (2016b), Grahm *et al*. (2015) and references therein. Grahm *et al*. (2015) provides a more extensive discussion of the performance of the DOMPLU experiment.

The discussion of the performance of DOMPLU components during installation covers only the most significant design specifications and consideration of compliance with the most significant aspects of the design basis. Extensive Quality Control was used to confirm compliance with the design basis and is discussed in more detail in Grahm *et al*. (2015).

### 6.4.1 Monitoring of Pressure on the Formwork

The results of the monitoring of the pressures on the formwork during concrete curing are shown in Figure 6.5. The maximum pressure at each location of the sensors develops rapidly, just a few hours after the concrete has been poured into the formwork and it reached the location of the sensors. This means that the hardening of concrete in the bottom has started even before the whole plug is cast, and that the maximum theoretical hydrostatic pressure of 160 kN/m$^2$ (in the bottom) will not occur. Instead, the maximum form pressure was typically less than 35 kN/m$^2$ measured at all sensor positions. A peak in the pressure recorded by the topmost sensor is also illustrated in Figure 6.5. This is thought to be related to the processes used during the final stages of concrete emplacement (i.e. a pressure increase from the concrete pumps).

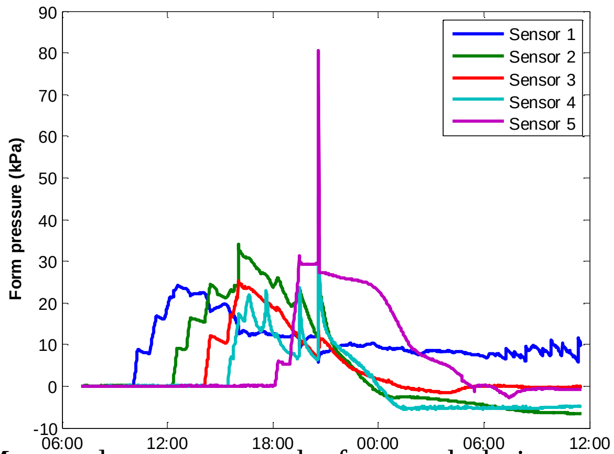



**Figure 6.5**: Measured pressures on the formwork during concrete curing. From Grahm *et al.* (2015).

### 6.4.2 Monitoring of Temperature in the Concrete Dome

The temperature in the concrete dome was controlled using the cooling system. Three stages of cooling were applied to the concrete:

- Stage A: The concrete dome was cooled to reduce the impact of hydration heat on concrete temperature.
- Stage B: The concrete dome was cooled to force its release from the rock.
- Stage C: Prior to contact grouting a third phase of cooling was applied to pre-stress the concrete.

The three stages of cooling are illustrated in Figure 6.6.

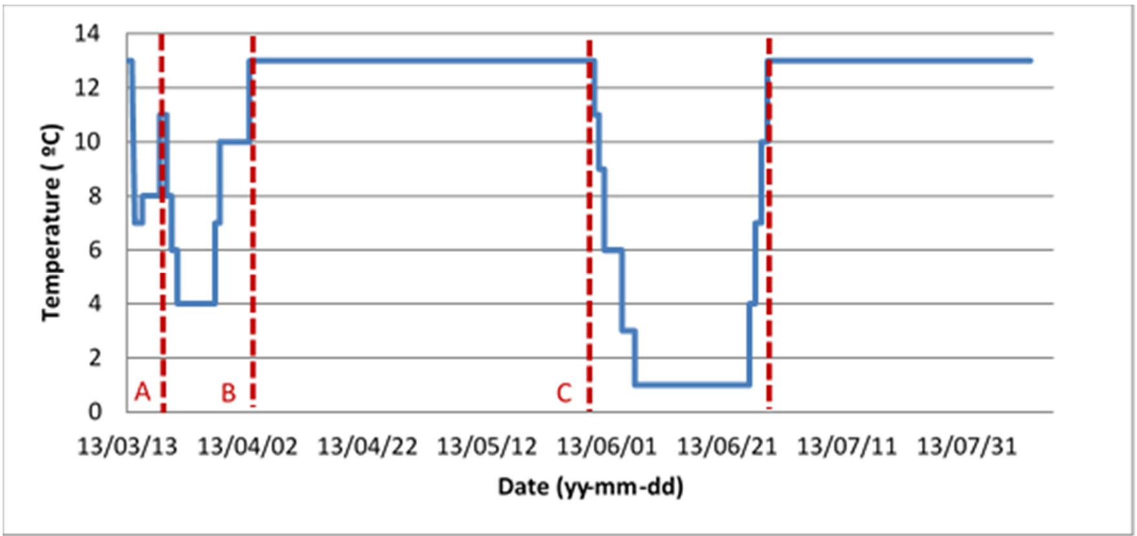



**Figure 6.6**: Illustration of the cooling sequence applied to the DOMPLU experiment concrete dome. From Grahm *et al.* (2015).

The temperature of the concrete dome was measured with 18 embedded sensors that were combined to measure both temperature and strain. The measured temperature variation is shown in Figure 6.7. The cooling sequence was successful in limiting the maximum temperature in the concrete during hydration. The maximum temperature was just below 18ºC, i.e. below the maximum temperature of 20ºC specified in DOMDS09 (Table 6.1).

During the second cooling stage, when the temperature in the cooling pipes was reduced to 4ºC, the corresponding temperature in the concrete dome varied between 6 -10 ºC depending on the location of the sensor (Figure 6.7).

In the final cooling stage, which was performed prior to contact grouting, the temperature in the cooling pipes was reduced to 1 ºC. This resulted in a temperature in the concrete dome of approximately 3-8ºC depending on the location of the sensor (Figure 6.7).

The measured temperature corresponds well to numerical predictions of the concrete temperature (Figure 6.8). The difference between the measured and predicted temperature is in general less than 2ºC, and this corresponds to periods when the cooling system was turned off and the temperature was affected by the ambient air temperature (variations of which were not accounted for in the numerical predictions).

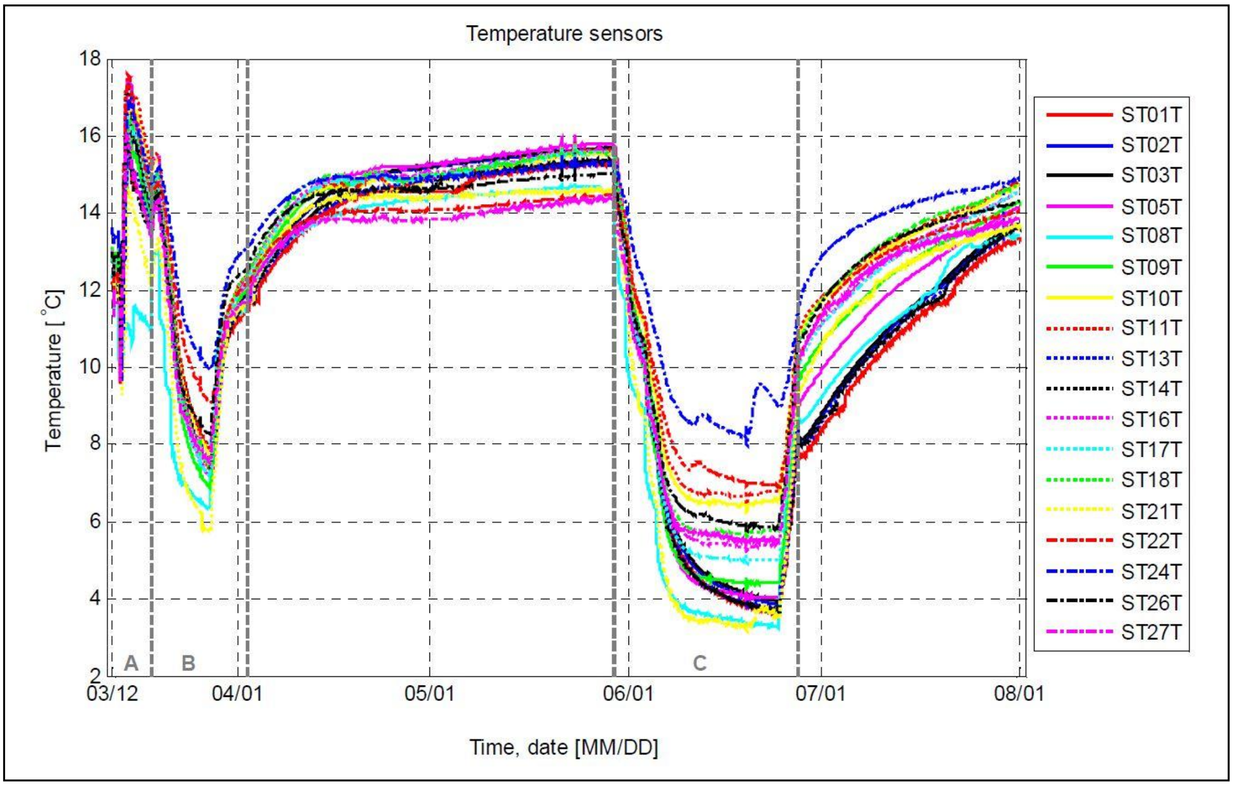



**Figure 6.7**: Measured temperature in the concrete dome from casting until the cooling system was turned off after concrete grouting. From Grahm *et al.* (2015).

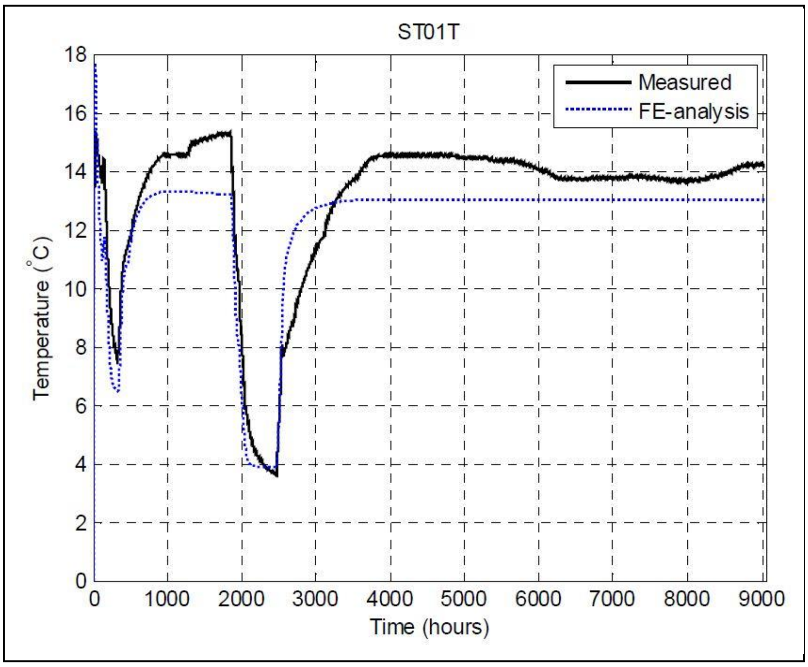



**Figure 6.8**: Comparison of the predicted and measured temperature in the concrete dome. From Grahm *et al.* (2015).

### 6.4.3 Release of the Concrete Dome from the Rock

Twenty-seven strain gauges measuring the variation in strain were embedded in the concrete dome (see Grahm *et al*., 2015 for further details). The measured strain for the embedded strain gauges for the period between casting to the date when the cooling was stopped is shown in Figure 6.9. In the figure, the three cooling stages are also illustrated. It can be seen that all sensors show the same type of behaviour, where the variation in measured strain is clearly dependent on the variation in temperature. This indicates that the concrete dome has released from the rock at least partially. If the concrete dome were completely bonded to the rock, then there would only be small variations in strain due to the cooling. On the other hand, if it had released completely from the rock in the upper part of the dome, then a significant decrease in strain would be visible at the time of release of the restraining forces. No such drop can be found in the results for the strain gauges. Based on the monitoring of strain, it was concluded that the concrete dome had at least partially released from the rock.

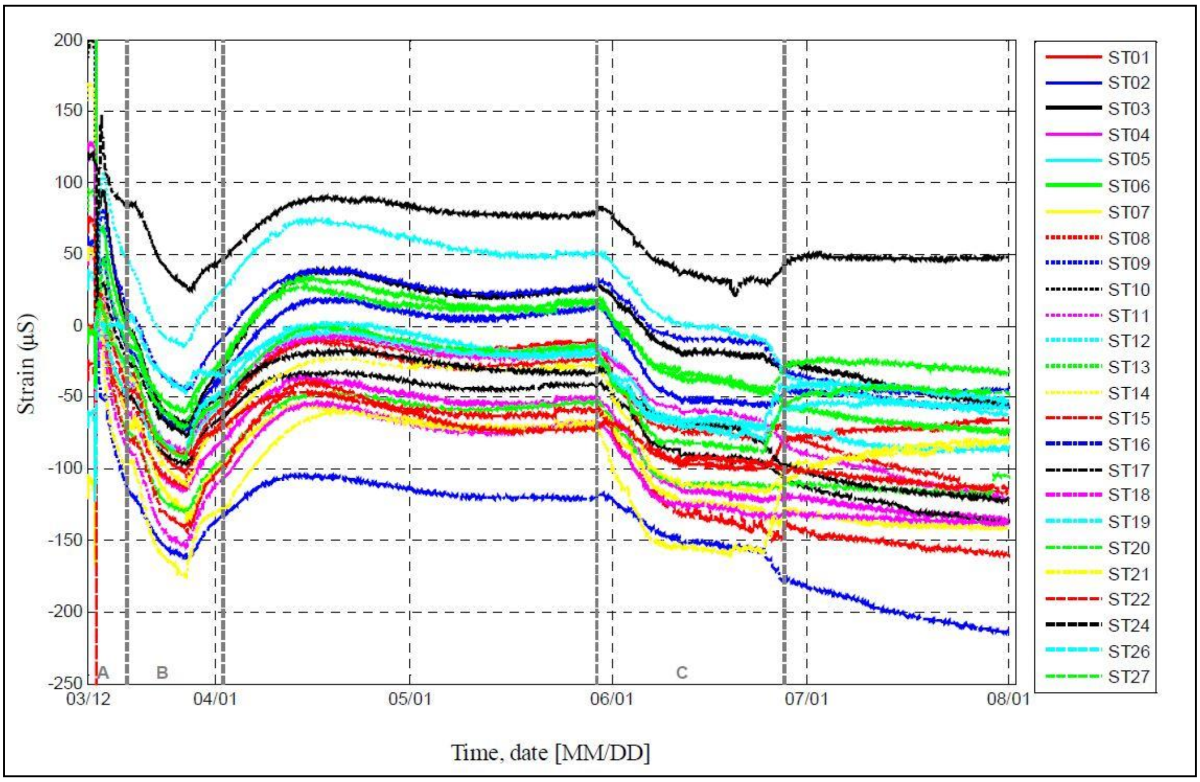



**Figure 6.9**: Variation in the strain in the concrete dome in the period from the start of casting until the system was turned off after contact grouting. From Grahm *et al.* (2015).

As well as using strain gauges to evaluate the release of the concrete dome from the rock, an analysis of the difference in strain prior to, and after, Stage C of the cooling sequence was undertaken. Measured strains were converted to compressive pre-stress by multiplying the difference in strain by the elastic modulus of the B200 concrete, and these pre-stresses were compared to the theoretical maximum pre-stress. The results of the comparison are presented in Figure 6.10. The analysis demonstrated that the concrete dome is on average pre-stressed to approximately 53% of the value that would be obtained if it had fully released prior to contact grouting. Only one sensor was pre-stressed to its maximum value (12 in Figure 6.10). The five sensors showing highest pre-stress compared to the theoretical value were all located on the downstream side of the dome. Based on this analysis it was concluded that the dome plug had partially released from the rock and that the downstream side of the slot released to a greater extent than the upstream side.

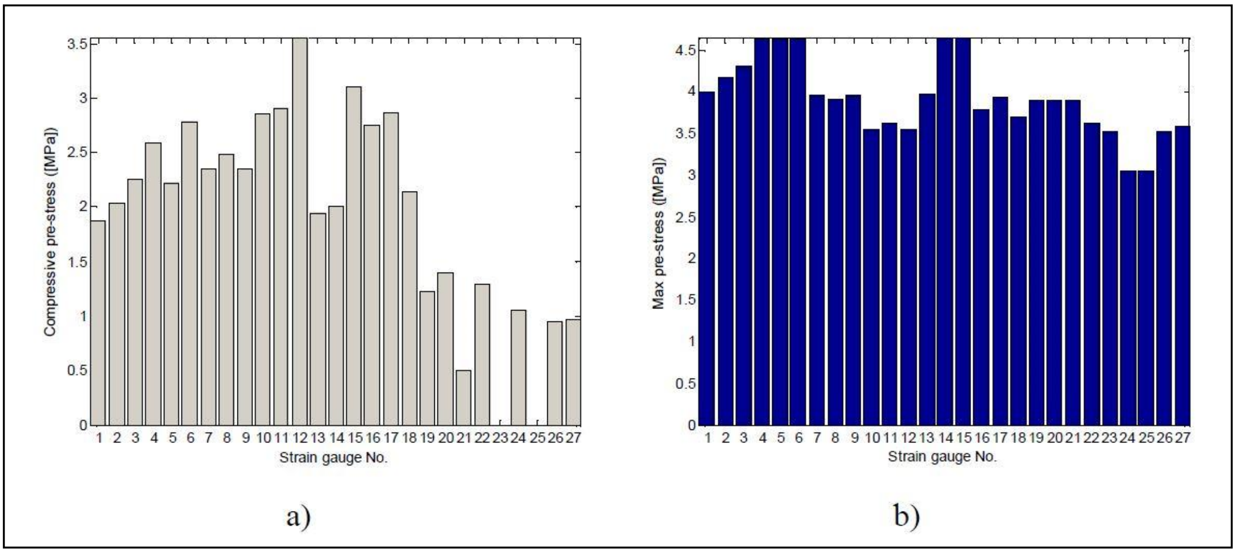



**Figure 6.10**: Measured (a) and predicted (b) maximum stress in the concrete dome owing to cooling and contact grouting. From Grahm *et al.* (2015).

## 6.5 Evaluation of Performance of DOMPLU Components during Pressurisation

In this section the performance of the DOMPLU experiment following pressurisation is evaluated with respect to the design specifications listed in Table 4.1:

- Section 6.5.1 discusses the monitoring of relative humidity, which contributes to the compliance assessment for DOMDS02 and DOMDS04.
- Section 6.5.2 discusses the monitoring of total pressure and pore pressure, which contributes to compliance with DOMDS01, DOMDS02, DOMDS04, DOMDS06 and DOMDS11.
- Section 6.5.3 discusses the monitoring of displacement, with respect to DOMDS03 and DOMDS05.
- Section 6.5.4 discusses the measurement of leakage across the plug, with respect to DOMDS13.

The water pressurisation sequence is illustrated in Figure 6.11 and is described in Table 6.2. In order to build confidence in the modelling of the performance of the deposition tunnel plug, the results of the monitoring have been compared to the results of numerical models. Some of the comparisons are provided below; not all comparisons are shown but further details are available in Grahm *et al.* (2015). Comparisons of the monitoring results with the results of the models helps in validation of the models, and may allow the modelling to be used in the future to demonstrate compliance with requirements.

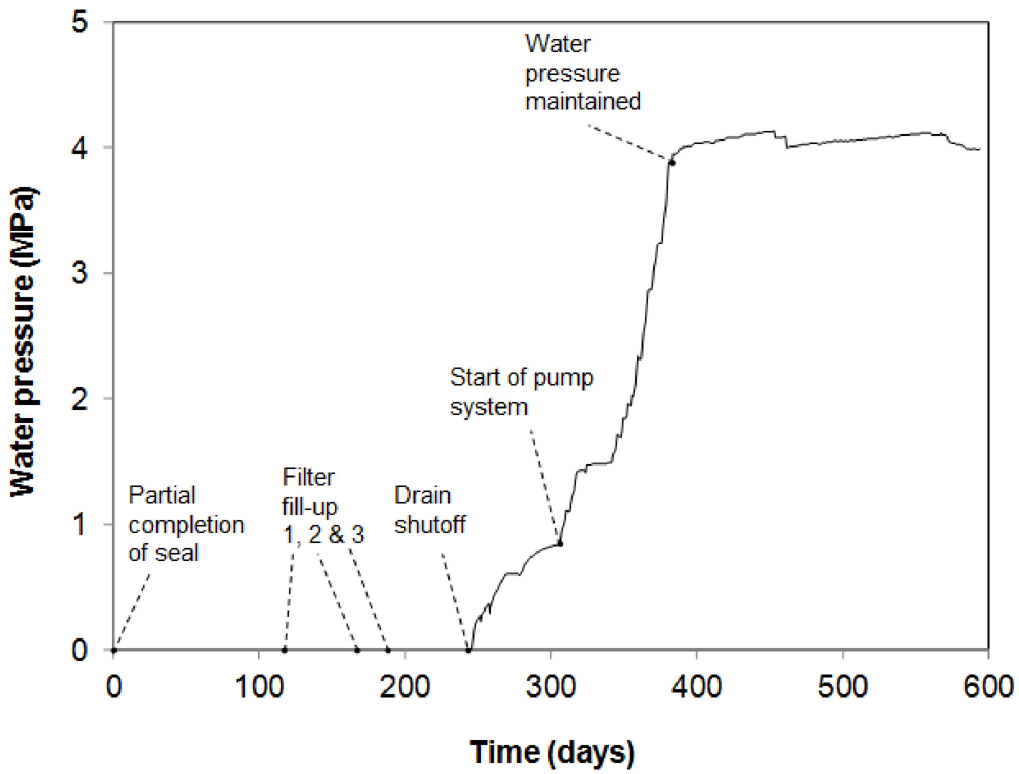



**Figure 6.11**: DOMPLU experiment pressurisation sequence. From Grahm *et al.* (2015).

**Table 6.2**: Summary of the pressurisation of the DOMPLU experiment.

| Date | Day (From Start of Monitoring) | Activity |
|---|---|---|
| 30 January 2013 | 1 | All sensors connected to the data acquisition system |
| 27 May 2013 | 117 | Test of filter saturation and draining |
| 11&19 June 2013 | 132 and 140 | Contact grouting |
| 16 July 2013 | 167 | Test of filter saturation and draining |
| 6 August 2013 | 188 | Filter saturation |
| 30 September 2013 | 243 | Filter drain shut-off, pressurisation of experiment by natural groundwater inflow commenced |
| 2 December 2013 | 306 | Water pumps turned on to commence artificial pressurisation of the experiment |
| 17 February 2014 | 383 | Water pressure reached 4 MPa |
| 30 September 2014 | 608 | Data freeze |

### 6.5.1 Relative Humidity

Monitoring of the relative humidity in the bentonite allows estimation of the water content and the degree of saturation, and thereby demonstration that the delimiters are functioning as specified (Table 6.1). A total of sixteen relative humidity sensors were installed; eight in the backfill and eight in the bentonite seal. The results of the monitoring are shown in Figure 6.12 and Figure 6.13. By approximately Day 550, the relative humidity throughout the bentonite seal had reached 95-100 %, at some positions e.g. in Measuring Section 2 (at the top) and in Measuring Section 3 (at the bottom). In the backfill transition zone, relative humidity values in Section 6 were similar to those in the bentonite seal, with the values in Section 7, i.e. further from the filter section, were slightly lower (approximately 80-90%).

The monitoring of the relative humidity demonstrated that the bentonite seal and the backfill transition zone saturated relatively homogeneously over the tunnel cross section, thereby providing supporting evidence that the delimiters were open for drainage/water saturation water to pass and led to a relatively even distribution of water onto the bentonite materials.

### 6.5.2 Total Pressure and Pore Pressure

In order to monitor the development of swelling pressure and pore pressure, sensors were positioned in the bentonite seal and in the backfill. The results of the monitoring are illustrated in Figure 6.14 and Figure 6.15 respectively. Key observations from the measurements include the following:

- The monitored swelling pressure (total pressure-pore pressure) in the bentonite seal has increased with time and, by 30 September 2014, the swelling pressure was between 100 and 700 kPa.
- The monitored swelling pressure (total pressure-pore pressure) in the backfill has increased with time and, by 30 September 2014, the swelling pressure was between 100 and 1000 kPa.
- The two pore pressure sensors positioned in the slot between rock and concrete dome initially showed a pressure of 450 to 500 kPa prior to closing the drainage. Up to the point when the water pressure increased up to 4 MPa, pore pressure in the slot between the rock and the concrete dome was approximately the same as in the other regions of the experiment and matched the applied water pressure (see Figure 6.15). This shows that the bentonite seal was not water tight initially. However, as shown by the blue line in Figure 6.15 (sensor PDU0001), the pore pressure in the slot successively decreased even though the applied water pressure was maintained at 4 MPa, implying that the bentonite seal is starting to seal and is restricting water access to this location.

The monitoring of the total pore pressure provides further demonstration that the bentonite seal and the backfill transition zone saturated relatively homogeneously over the tunnel cross section, thereby providing supporting evidence that the delimiters were open for drainage/water saturation water to pass and led to a relatively even distribution of water onto the bentonite materials.

It is expected that the monitoring of the total pressure will contribute to demonstration that the bentonite seal will develop a swelling pressure of 2 MPa, but, by the time of the data freeze for this report (30 September 2014), the bentonite materials were yet to achieve their full swelling pressure (most parts of the seal still had a swelling pressure well below 500 kPa).

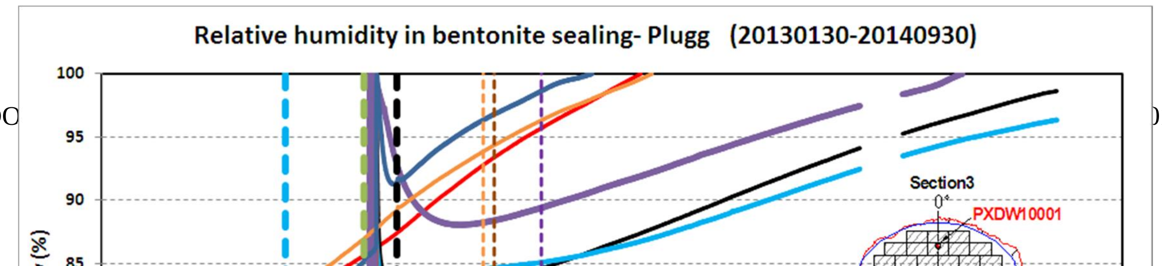


**Figure 6.12**: Relative humidity recordings in the bentonite seal. Specific steps in the pressurisation sequence (see Figure 6.11 and associated text) are identified as “No.1 through No.6”. From Grahm *et al.* (2015).

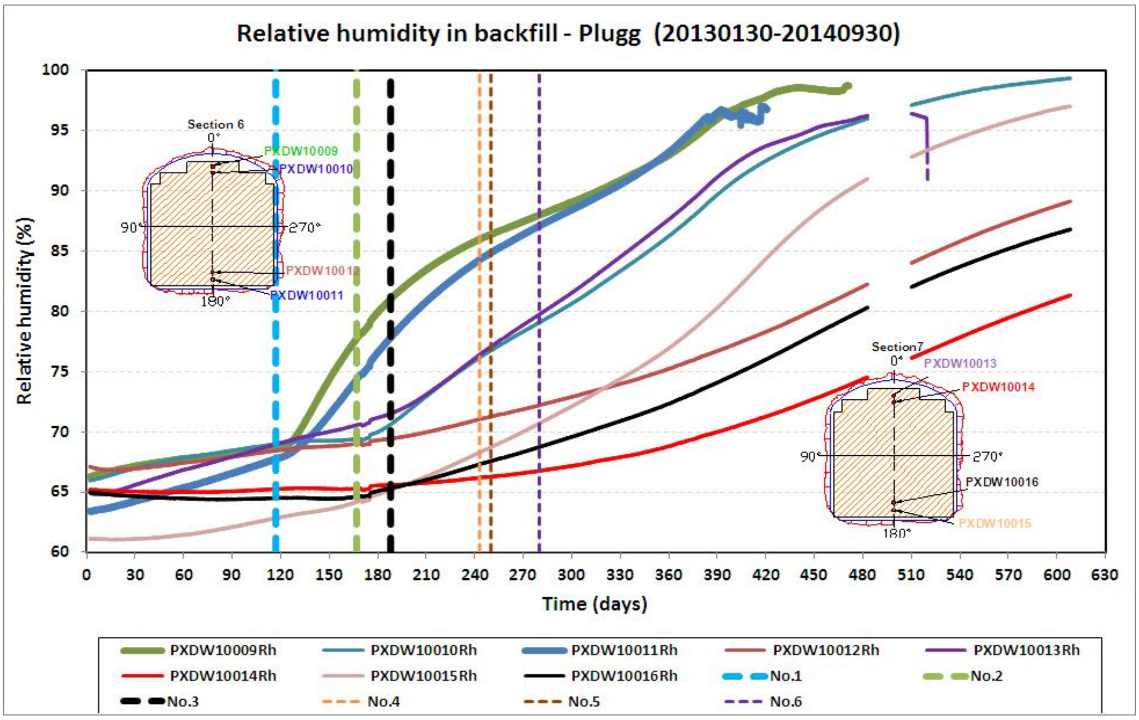



**Figure 6.13**: Relative humidity recordings in the backfill transition zone. Specific steps in the pressurisation sequence (see Figure 6.11 and associated text) are identified as “No.1 through No.6”. From Grahm *et al.* (2015).

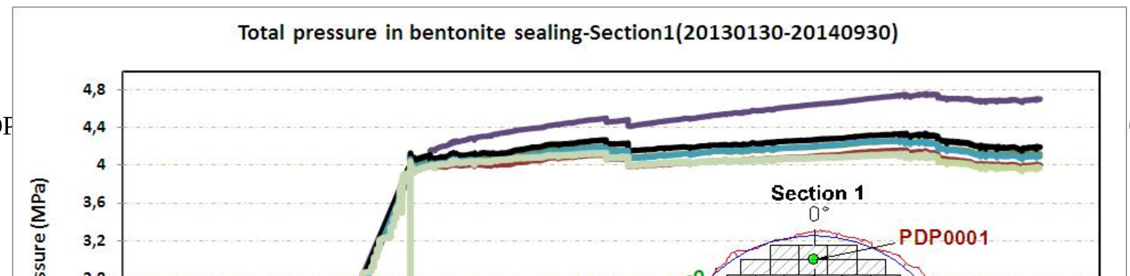


**Figure 6.14**: Total pressure measured in Section 1 in the bentonite seal. From Grahm *et al.* (2015).

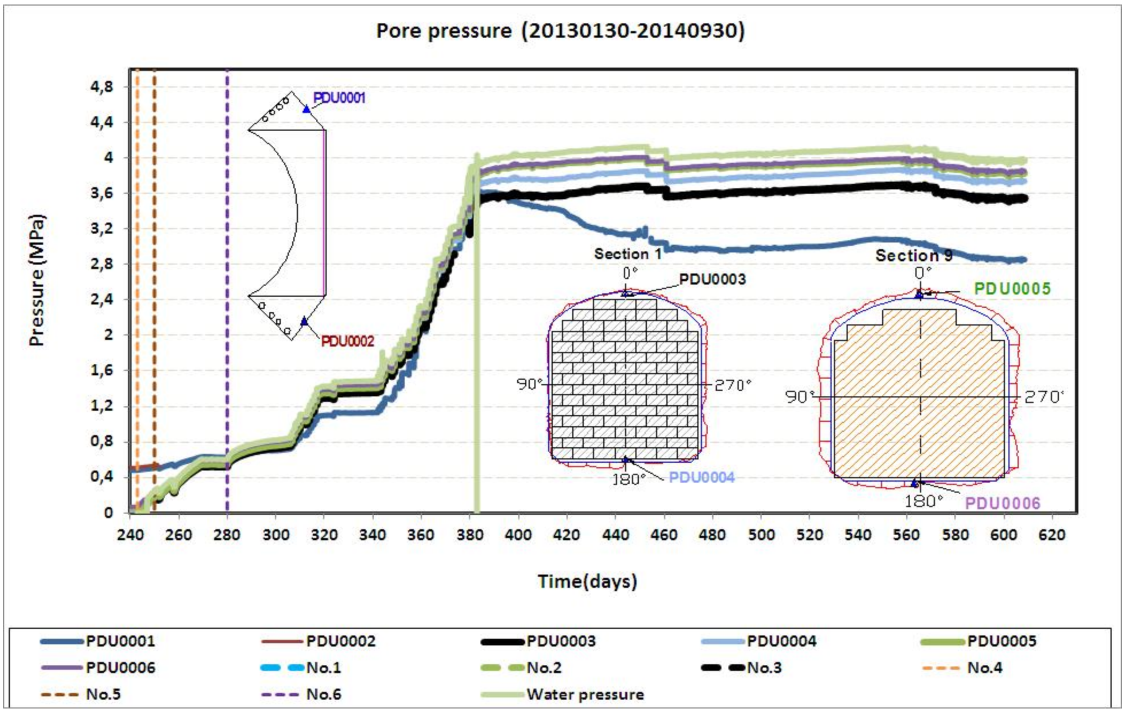



**Figure 6.15**: Recorded pore pressure between concrete and rock, between the bentonite seal and the rock (Section 1), and between the backfill transition zone and the rock (Section 9). From Grahm *et al.* (2015).

### 6.5.3 Displacement

The results from the measurements of displacement are shown in Figure 6.16. In the figure, it can be seen that all three displacement sensors have registered a movement inwards i.e. the bentonite seal has swelled and compressed the gravel filter and the pellet filled slot inside the LECA® beam wall. In total, displacement of approximately 30 mm was registered from the start of the test start until Day 385.

A comparison of the measured displacements with predictions based on numerical models is presented in Figure 6.17. The nature and magnitude of the displacements match well, with discrepancies explained by variations in the assumed geometry of the numerical model and the actual geometry adopted in the DOMPLU experiment.

The monitoring of displacement provides confidence that the delimiters are behaving as required (DOMDS03 and DOMDS05) and that the plug is behaving as designed. Furthermore, the correlation of the predicted displacements with the measured values provides confidence in the numerical analyses underpinning the plug design.

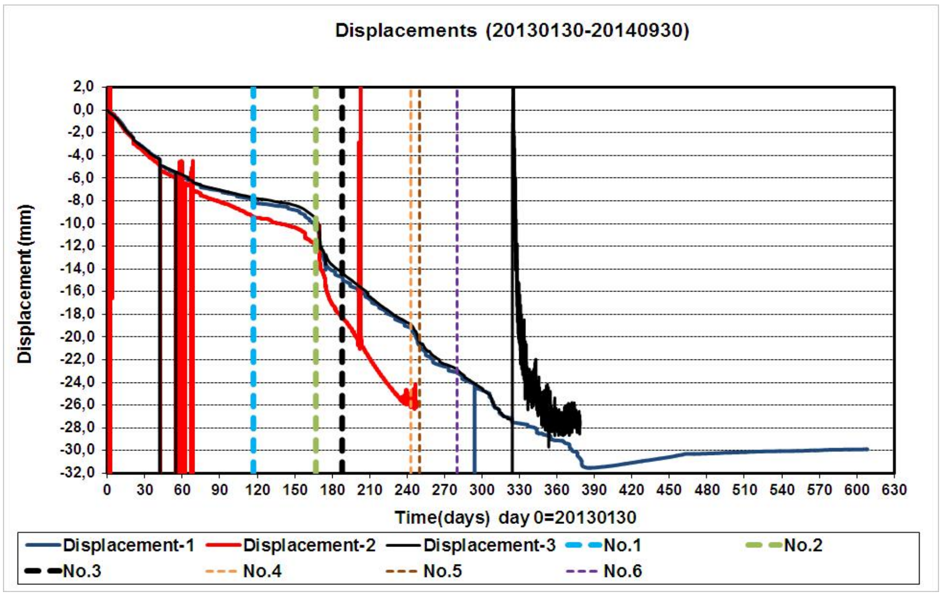



**Figure 6.16**: Measured displacement of the seal (2) and LECA® beams (1 and 3) respectively, relative to the concrete back wall. From Grahm *et al.* (2015).

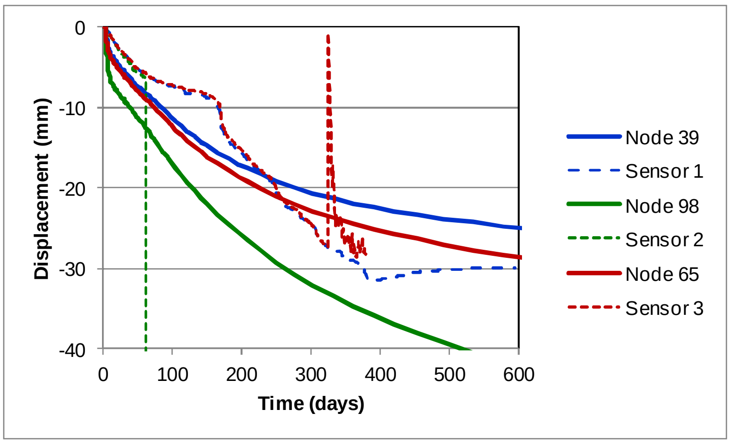



**Figure 6.17**: Comparison of the measured displacements with predictions based on numerical models. From Grahm *et al.* (2015).

### 6.5.4 Leakage

Several different methods were used to measure the leakage across the plug. The primary method automatically transfers seepage water from a water collection weir to a scale that weighs the leakage mass for on-line recording. In addition to this, manual measurements were introduced to record the experiment-related leakages that started to occur at high pressure: a water escape via the sensor cable bundle within the concrete dome and a water escape via a rock fracture.

The pressurisation system was started on 2 December 2013 (day 306). The pressure was increased by up to 2.5 bar every week. The plug system was almost watertight until the pressure reached approximately 31 bar (3.1 MPa). After this, water bearing fractures opened in the rock and also in the concrete dome via the main cable bundle and significant leakages were recorded.

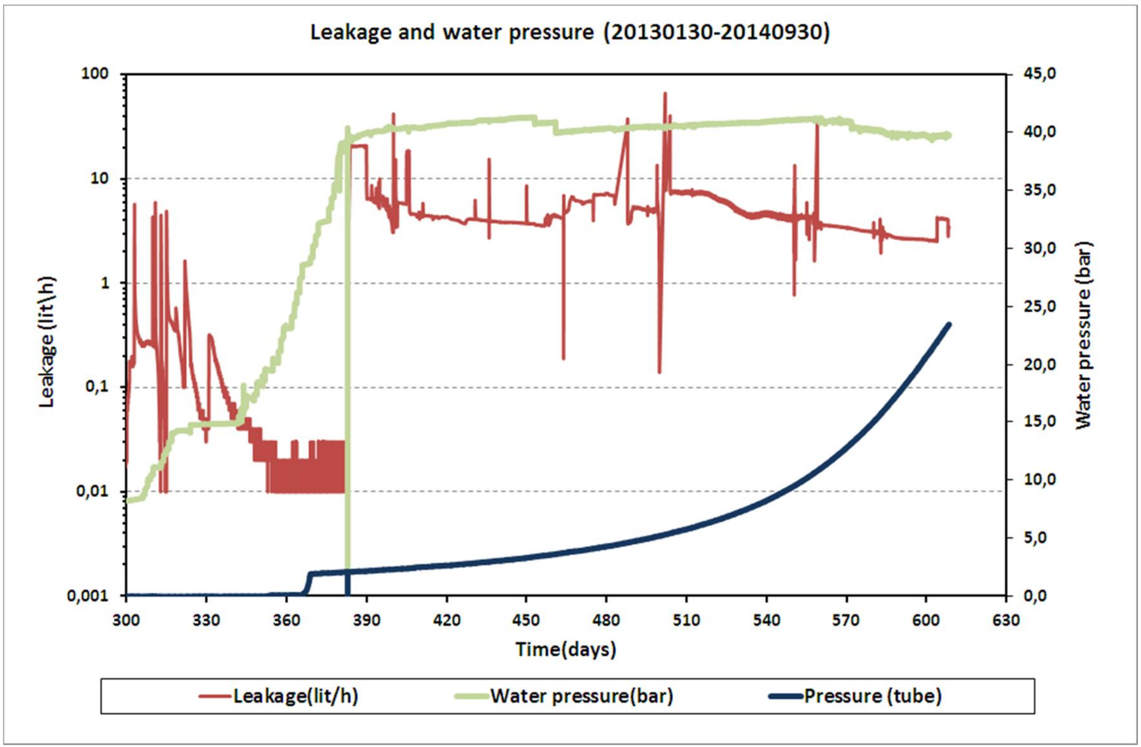



**Figure 6.18**: Measured leakage from the weir and the applied water pressure. From Grahm *et al.* (2015).

These experiment-related leakages were measured manually every week. They increased exponentially when increasing the water pressure (i.e. hydraulic jacking). Consequently, it was decided to continue operation and monitoring at a stable pressure (of 4 MPa). Leakage past or around the plug was recognised as a project risk but does not compromise the basic goals of the DOMPLU experiment. Running the test at 4 MPa is a realistic worst-case scenario for a groundwater pressure during operation of the Spent Fuel Repository since it approximates the natural hydraulic head at repository depth and thus is a reasonable pressure target for the DOMPLU experiment.

The leakage from both the fracture in the rock and from the cable bundles was diverted in order not to be collected in the weir and was measured manually. The results from the manual leakage measurements are shown as a complement to the results from the on-line recordings from the weir in Figure 6.18. As seen in Figure 6.19, all leakages decreased substantially with time up to the data freeze date of 30 September 2014. The total inflow to keep 4 MPa water pressure was about 400 ml/min, and, at this time the measured leakage was distributed as follows (note that leakage is expressed as percentage of inflow in the brackets):

- Rock fracture 169 ml/min (42% of inflow).
- Weir 43 ml/min (11% of inflow).
- Cable bundle 8.5 ml/min (2% of inflow).
- Remaining rock mass 178.5 ml/min (45% of inflow).

In the eight month period following the stabilisation of the water pressure at 4 MPa, the leakage rate steadily reduced. By 30 September 2014 (Day 608), the recorded leakage rate collected in the weir was about 2.6 litres per hour (0.043 l/min). Initially, about 1.0 l/min injection water was needed to keep the 4.0 MPa water pressure in the filter. After eight months of plug system operation, only approximately 0.4 l/min was needed to maintain the same pressure.

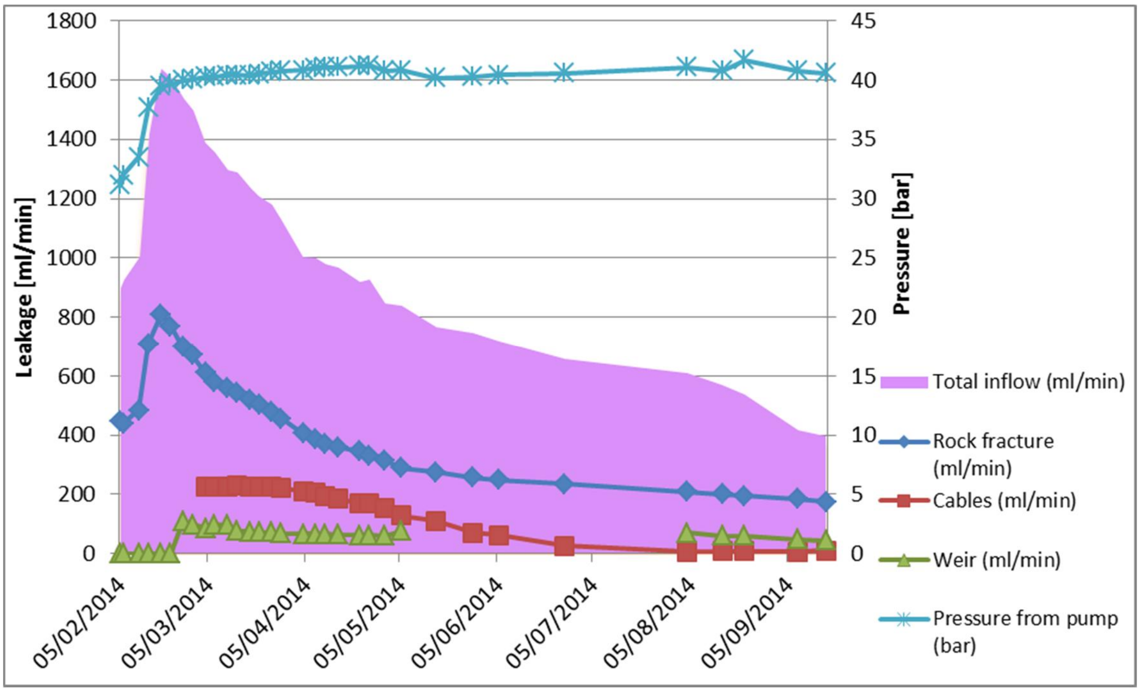



**Figure 6.19**: Measurements of leakage together with total water injection flow needed to keep the water pressure stable near at 4 MPa (about 40 bar). From Grahm *et al.* (2015).

## 6.6 Evaluation of the DOMPLU Experiment Monitoring System

A parameter-by-parameter evaluation of the monitoring system, is provided in Table 6.3. Overall, the monitoring system has been adequate and only a few of the sensors have failed. The results from the monitoring system help to support the validation of the modelling results and contribute to the overall understanding of the performance of the DOMPLU experiment.

**Table 6.3**: Evaluation of the DOMPLU experiment monitoring system. Further information is available in Grahm *et al.* (2015).

| Sensor | Parameter(s) | Evaluation |
|---|---|---|
| Wika S11 Pressure Sensors | Pressure on the formwork | The sensors performed well and were able to demonstrate that concrete hardening commenced before the whole plug had been cast. |
| TML KM-100 AT and Geokon 4200 | Strain and temperature in the concrete dome | The two different sensors both performed well and gave similar results with a difference of less than 0.5°C. Three of the sensors failed, possibly as a result of grout infiltration. The Geokon sensors suffered from occasional voltage spikes which had to be filtered out from the results. A key issue with the strain sensors was determining the point at which the sensor is fully bonded to the concrete. This was defined as the time when the output signal stabilised. |
| Aitemin SHT75 V3 | Relative humidity in the bentonite seal and backfill | The sensors were able to detect the response to the different stages of filling of the filter and pressurisation of the experiment. One of the sensors in the bentonite seal failed, but the sensors were able to monitor the saturation of the bentonite up to 95-100% saturation when the results are difficult to interpret and the sensors stop functioning. |
| Geokon 4800-1x-10 MPa | Total pressure in the bentonite seal and backfill | The total pressure sensors were able to track the development of total pressures in the bentonite seal and backfill. One of the sensors recorded high pressures (15 MPa after 380 days), and was judged to have failed. |
| Geokon 4500SH-3-10 MPa | Pore pressure in the bentonite seal and backfill | The pore pressure sensors were able to track the development of pore pressures in the bentonite seal and backfill, including the shut-off of drainage on Day 243 (see Figure 6.6). |
| Geokon 4435-1X-50 | Displacement of the delimiters and filter | The displacement sensors measured displacements of approximately 30 mm up to Day 385 when the sensors failed. Failure is thought to be a result of the measurement range being exceeded. |
| Leakage water measurements | Leakage across the concrete plug and concrete-rock interface | The measurement of leakage across the plug has allowed quantification of water flows and separation into the location(s) through which water has moved (including the rock). |

## 6.7 Assessment of Compliance with the Design Basis and Evaluation of the Results with Respect to the Experiment Objectives

In this section we discuss the results from the DOMPLU experiment with reference to:

- Compliance with the safety functions presented in Section 6.1.1 is discussed in Section 6.7.1.
- Compliance with the design specifications listed in Table 6.1 is discussed in Section 6.7.2.
- The outcomes of the experiment with respect to the objectives presented in Section 6.2.1 are discussed in Section 6.7.3.

### 6.7.1 Compliance with the Deposition Tunnel Plug Safety Functions

Conduct and evaluation of the DOMPLU experiment is not yet complete and all statements regarding compliance with the safety functions reflect the current observations. Additional analysis after experiment dismantling will be used to further assess the compliance to the safety functions.

However, based on the results of the experiment to date, the following can be concluded with regard to the compliance of the DOMPLU design to the safety functions of SKB's reference deposition tunnel plug:

- *Confine the backfill in the deposition tunnel*: This safety function is related the requirement on the concrete dome to be kept in place. Displacement sensors on the concrete dome surface showed that differences in its position during pressurisation are negligible (Grahm *et al*., 2015). In addition, monitoring of small inward displacements of the filter provide additional evidence that the backfill is held in place. Therefore, based on the information available to date, it can be concluded that DOMPLU is performing according to this safety function.
- *Support saturation of the backfill*: The DOMPLU experiment does not specifically address saturation of a deposition tunnel backfill, but saturation of the backfill transition zone that is included in the DOMPLU experiment can be used to infer the performance of the reference design with respect to this safety function. As shown in Figure 6.13, the relative humidity of the backfill transition zone increases in response to the filling of the filter zone with water, and, backfill pore pressure increases rapidly in response to pressurisation of the filter and a water pressure gradient is established within the plug system, indicating that the plug is supporting saturation of the backfill.
- *Provide a barrier against water flow that may cause harmful erosion of the bentonite in the buffer and backfill*: This safety function is linked to a design specification that is currently defined as "reduce the leakage across the plug to be as low as possible". Leakages occurred, but through a route used for a monitoring cable, and suitable design will ensure that this would not happen in a repository. No other leakages of bentonite were detected, although leakages of bentonite into the filter will be checked during the dismantling of the experiment. Recent calculations predict a leakage of 0.1 litres/minute across the plug. 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 litres/minute), suggesting that, based on the information available to date. this safety function should be met by the deposition tunnel plug design tested in the DOMPLU experiment.

The compliance of DOMPLU with the safety functions is also met by linking the safety functions to more detailed requirements (design specifications). Evaluation of the performance of the DOMPLU experiment with respect to the design specifications is described in Section 6.7.2.

### 6.7.2 Compliance with Design Specifications on the DOMPLU Experiment

An evaluation of the compliance of the DOMPLU experiment with the design specifications presented in Table 6.1 is presented in Table 6.4. The implications are discussed in Section 6.7.3.

**Table 6.4**: Compliance assessment for key design specifications on the DOMPLU experiment. The feedback to the design basis is discussed further in the text.

| ID | Requirement / Design Specification | Compliance Assessment | Feedback to Design Basis |
|---|---|---|---|
| DOMDS01 | The backfill transition zone shall reduce the swelling pressure coming from the backfill in accordance with the swelling pressure acting on the concrete dome being a maximum of 2 MPa. | By the time of the data freeze, the swelling pressure in the backfill transition zone was between 100 and 1000 kPa (see Section 6.5.2). The rate of swelling pressure development was slower than predicted. Further monitoring of the pressure in the backfill transition zone will be required to evaluate compliance with this requirement. | The concrete dome design resists very high load. However, it is favourable to limit the swelling pressure acting on the dome to 2 MPa. Thereby a load safety factor of two is obtained, ensuring that the highest safety class for concrete structures can be achieved. |
| DOMDS02 | The delimiter separating the backfill and filter shall be open for drainage/saturation water to pass in both directions. | Monitoring of relative humidity and pore pressure (see Sections 6.5.1 and 6.5.2) demonstrated that saturation was relatively homogeneous. | This requirement appears appropriate to maintain within the design basis. The experiment has demonstrated that LECA® is a good material from the perspective of hydraulic conductivity. |
| DOMDS03 | The delimiter separating the backfill and filter shall be capable of displacement in response to swelling of the seal and backfill. | Monitoring of displacement demonstrated that the delimiter was displaced in response to swelling of the bentonite seal (see Section 6.5.3). | This requirement appears appropriate to maintain within the design basis. |
| DOMDS04 | The delimiter separating the gravel filter and the bentonite seal must allow water from the filter to flow through it, evenly distributed over its entire cross section. | Monitoring of relative humidity and pore pressure (see Sections 6.5.1 and 6.5.2) demonstrated that saturation was relatively homogeneous over the tunnel cross section. | This requirement appears appropriate to maintain within the design basis. The experiment has demonstrated that geotextile is a good material from the perspective of hydraulic conductivity. |

| ID | Requirement / Design Specification | Compliance Assessment | Feedback to Design Basis |
|---|---|---|---|
| DOMDS05 | The delimiter separating the filter and the bentonite seal shall be capable of displacement to facilitate compaction of the filter in response to swelling of the bentonite seal. | Monitoring of displacement demonstrated that the delimiter was displaced in response to swelling of the bentonite seal (see Section 6.5.3). | This requirement appears appropriate to maintain within the design basis. |
| DOMDS06 | 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). | The swelling pressure achieved by the bentonite seal developed slowly but quite consistent with model predictions (see Section 6.5.2), and, 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. |
| DOMDS07 | Low-pH concrete that generate a leachate with a pH ≤11 shall be used | 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 the concrete dome or to all cementitious materials). |
| DOMDS08 | The concrete shall have a compressive strength of 54 MPa (at age of 90 days), maturity conditions according to Swedish standard regulations. | Compliance with the compressive strength requirement was met through testing of the B200 concrete mix (see Section 6.2.2 and Figure 6.4). | This requirement appears appropriate to maintain within the design basis. |
| DOMDS09 | The temperature in the concrete dome shall not exceed 20°C during curing. | Compliance with this requirement was demonstrated by the monitoring of the temperature in the concrete dome. The maximum temperature reached was just below 18ºC (see Section 6.4.2 and Figure 6.7). | 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. |

| ID | Requirement / Design Specification | Compliance Assessment | Feedback to Design Basis |
|---|---|---|---|
| DOMDS10 | A sequential cooling process shall be performed to contract the concrete dome prior to and during contact grouting. | Temperatures in the concrete dome were measured in response to the temperature of the cooling water. The contraction of the concrete dome was checked through monitoring of displacement and strain and through comparison of the theoretical pre-stress with the actual pre-stress derived from the strain monitoring. This monitoring demonstrated that the achieved pre-stress of the dome was only 53% of the expected value if the concrete dome had fully released from the host rock (see Section 6.4.3). | The compliance approach for this requirement will only result in inspection of the forward part of the contact. The requirement could be modified to reflect this reality.<br><br>The monitoring showed good agreement with the use of computational models. It is expected that there will not be a requirement for monitoring to verify this requirement in the Spent Fuel Repository.<br><br>Furthermore, the results of the DOMPLU experiment have shown that the shrinkage of the young concrete was lower than predicted, and, therefore, it may not be necessary for the concrete dome to contract so much that it fully detaches from the rock. Further evaluation of the results from DOMPLU will be undertaken and fed back into the design basis. |
| DOMDS11 | The full pressure against the concrete dome must not appear until it has cured and gained sufficient strength. | Water pressure inside the filter was carefully monitored and controlled during concrete curing.<br><br>Monitoring of the pressure of the bentonite seal showed that significant swelling of the bentonite did not develop until the concrete plug had cured and gained strength. | Review of the compliance of the design basis during the project noted that this is an appropriate requirement but it should be modified to provide a period over which the dome should not experience significant pressure, and that “full pressure” replaced with “significant pressure”. |

| ID | Requirement / Design Specification | Compliance Assessment | Feedback to Design Basis |
|---|---|---|---|
| DOMDS12 | The plug shall resist the sum of the hydrostatic pressure at repository depth and the swelling pressure of the backfill until the main tunnel is filled; 5 MPa water pressure and the swelling pressure from the backfill in the section adjacent to the plug. Currently, the backfill swelling pressure is assumed to be 2 MPa with the help of backfill transition zone that decreases the load from a high load to 2 MPa. | The DOMPLU test did not demonstrate this requirement, as the system has only been pressurised to ~4MPa within the DOPAS Project at which time there was significant leakage occurring through the near-field rock and other locations.<br><br>However, the experimental results were shown to be consistent with numerical modelling of the plug structure, providing confidence in the numerical modelling. The results of the numerical modelling were consistent with this requirement. | The design basis can probably be modified with a less highly-conservative water pressure value identified.<br><br>As part of on-going work in the DOMPLU Project, a future strength test, at a higher test pressure, can be performed before plug breaching and retrieval of the plug components. |
| DOMDS13 | Reduce the leakage across the plug to be “as low as possible”. | 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.<br><br>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.<br><br>The experimentally-related water escapes recognized at Äspö HRL are judged to be very unlikely in Forsmark. |
| DOMDS14 | Provide a barrier against air and vapour transports, to and from the deposition tunnel. | A simple water supply system was connected to the drainage pipes and thereby the bentonite seal got access to water as soon as possible. This process was carefully monitored by pore pressure and relative humidity sensors. | It is believed that a saturated bentonite seal will ensure gas tightness of the plug system. At the time of the data freeze of this project the seal was not fully saturated.<br><br>The feedback to the design basis is that the gas tightness requirement cannot be assured within the first couple of years from plug construction. |

### 6.7.3 Outcomes of the Experiment with Respect to the Objectives

The objectives of the experiment were presented in Section 6.2.1. The outcomes of the experiment with respect to these objectives are discussed in this sub-section.

*Finalise the details of the reference design*

The DOMPLU design has performed well. New materials tested in the experiment, such as LECA® beams, geotextiles and cross-cut plastic grouting pipes, might be implemented in a modified reference design. However, confirmation of the performance of these materials, must be further examined during dismantling of the DOMPLU experiment at a future date. This will include checking the acceptability of these materials from a post-closure safety point of view during the detailed design phase.

The comparison between monitoring results and modelling predictions has shown that the current understanding of the system is sufficient to develop predictive models. This provides additional confidence in the application of existing modelling approaches during the detailed design phase.

*Demonstrate the feasibility of plug installation*

The pressure measurements during casting showed that a future formwork can be built with thinner dimensions. An improved routine should also be developed for positioning of the frame of the formwork, especially regarding the extension with fitting pieces to the rock and introduction of a manhole in the design.

The concrete used was good quality and its behaviour was as expected of the B200 concrete. The results of the DOMPLU experiment have demonstrated that reinforcement can be removed from the design of the concrete dome; unreinforced concrete can be used. The use of unreinforced concrete will improve the rate at which deposition tunnel plugs can be emplaced in the repository.

Measurement of concrete properties (e.g., compressive strength) was shown to be consistent with on-site measurement of test blocks. An exception to the initial expectations was that the concrete was found to have a high air content (6-9%) at delivery which was probably related to the mixing of additives and the long transport. Another exception was the lower amount of autogenous shrinkage, which likely was caused by the higher air content.

The cooling procedure was successful and can be specified in detail for future plugs. The redundant cooling machine was never needed but it is considered important to have a spare cooler on site in case the operating machine fails.

The installation of the cooling pipes and grouting tubes was time consuming and difficult, so a more efficient practices will be required for the future repository. The contact grouting procedure, in combination with cooling, worked as intended and the leakage monitoring indicated that the grout made the plug watertight enough for the initial pressure increments.

The DOMPLU experiment demonstrated the successful use of a filter to control groundwater pressure acting on a concrete dome.

Further evaluation of the experiment will be undertaken when the plug is dismantled, for example the geometry and homogeneity of the watertight seal.

*Validate requirements on construction methods*

The good performance of the DOMPLU experiment has allowed construction methods to be validated. Monitoring of the concrete dome showed that there was not a sudden displacement of the concrete from the rock, i.e. a loss of adhesion as expected based on an expectation of high autogenous shrinkage of the low-pH B200 SCC. However, one reason why the concrete dome did not release fully from the rock, is that the autogenous shrinkage of the concrete dome was less than the observations in the material tests. If, through further analysis, this can be confirmed, it may no longer be a requirement that the concrete dome releases from the rock.

Several detailed observations on the requirements on construction methods were made during the conduct of the experiment and are documented in Grahm *et al*. (2015). Examples include:

- In the future, it may be necessary to add a requirement that the strength of the LECA® beams should be high enough for the installation process, i.e. the beams should be able to withstand the total pressure from behind the beams.
- Industrial process for construction of formwork is required for deployment in the repository.

*Demonstrate that the plug works as intended under realistic conditions*

This objective required testing 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.

The DOMPLU test did not fully demonstrate this objective, as the system has only been pressurised to ~4MPa within the DOPAS Project, at which time there was significant leakage occurring through the near-field rock and other locations. However, this is affected by the use of water at high pressure to pressurise the experiment, the presence of sensor cables and the lower quality of the rock at the DOMPLU experiment site in Äspö HRL compared to the planned repository at Forsmark.

*Develop a method for leakage measurement and use it to determine a leakage rate across the deposition tunnel plug.*

An appropriate prototype of a water collection system was developed for DOMPLU. The system records, with reliable on-line updates, the water leakage rate out of the pressurized region. However, the system is sensitive to evaporation and a plastic sheet was used to cover the concrete dome to reduce these effects. The sheet was connected to the weir.

This objective also required evaluation of whether a low enough hydraulic conductivity could be achieved (<0.1 l/min as discussed by Grahm *et al.*, 2015). After eight months of subjecting the dome plug a water pressure of 4 MPa, the leakage across the plug was about 0.043 l/min (2.6 l/h). This is well below the desired level of a leakage past the plug of less than 0.1 l/min. The measurements also show that the leakage rate may continue to follow a decreasing trend.

*Improve testing and quality control during repository construction.*

A basic design condition for the deposition tunnel end plug is that it shall be manufactured, installed and controlled based on proven technology. The installation must be made with high reliability, i.e. without risk for failure, and it should be possible to control the installation in relation to predetermined acceptance criteria. The DOMPLU experiment has proven to be a successful test of quality control during repository construction. Several existing quality control procedures were shown to be fit for purpose and some were shown to require improvement. Further details are provided in Grahm *et al.* (2015).

The DOMPLU experiment has been used to develop a construction procedure that shows it will take approximately 35 days to install each deposition tunnel plug to prepare casting of the concrete dome. The experience from the DOMPLU experiment can also be used to develop strict procedures with respect to operational safety.

## 6.8 Conclusions from the DOMPLU Experiment

The DOMPLU experiment has provided confidence that it is feasible to build the dome plug system. This includes verification of practical aspects such as logistics and arranging of parallel activities. Further analysis of the results, the on-going performance of the experiment and consideration of long-term issues will need to be undertaken to confirm that the design meets all aspects of the safety functions. It was also shown that it is possible to use an unreinforced concrete dome plug constructed from the low-pH SCC B200 mix in compliance with the design requirements. An advanced cooling scheme was successfully used to reduce the induced stresses in the concrete dome during hydration and to cause a thermal pre-stress prior to contact grouting.

Another crucial purpose of the experiment was to measure the water sealing function of the plug by subjecting it to a high water pressure. During the experiment there were issues related to water escape, partly through a fracture in the rock and partly via sensor cabling. This resulted in an operational limit for the water pressure at 4 MPa, although the original plan was to pressurize the plug to 7 MPa. By the end of September 2014, the pressure on the concrete dome had been sustained at 4 MPa for more than six months.

By this time, the measured leakage past the plug was 0.043 l/min. The measured leakage rate decreased with time and may continue to follow this trend. The results show that the water pressure on the concrete dome is decreasing while the water pressure upstream of the bentonite seal is constant. This observation, together with measurements of relative humidity and total pressure, shows that the bentonite seal is becoming more and more watertight. Subsequently, the leakage rate past the plug is expected to continue decreasing.

# 7 Posiva's Deposition Tunnel Plug

This chapter discusses the achievements in the DOPAS Project, in particular the design, construction and initial pressurisation of the POPLU experiment[8], with respect to Posiva's reference deposition tunnel plug and the development of the alternative wedge plug:

- In Section 7.1, the design basis for the reference deposition tunnel plug is described, focusing on the safety functions assigned to the plug, a summary of the reference design, and presentation of the key design specifications contained within the design basis and which are directly tested through measurement of the results of the POPLU experiment. More information on the design basis can be found in White *et al*. (2014).
- In Section 7.2, the POPLU experiment is described, including the objectives of the experiment, and a summary of the design work (including numerical modelling), construction of the experiment niche and installation of the POPLU components. More details on the construction of the POPLU experiment are in DOPAS (2016b) and in Holt and Koho (2016).
- Section 7.3 discusses the learning from the POPLU experiment with respect to the operational issues that will be faced during installation of Posiva's deposition tunnel plug.
- In Section 7.4, the performance prior to pressurisation of the POPLU components is evaluated, and conclusions drawn regarding the suitability of the materials and the emplacement methods used to install the materials for application in the repository.
- In Section 7.5, the performance during initial pressurisation of the POPLU components is evaluated, and conclusions drawn regarding the suitability of the materials and the emplacement methods used to install the materials for application in the repository.
- Section 7.6 evaluates the performance of the monitoring system used in the POPLU experiment and its applicability in repository monitoring.
- Section 7.7 presents an evaluation of the compliance of the POPLU experiment with the design basis, the feedback of the results to the design basis and discusses the learning outcomes from the work.
- Section 7.8 presents the overall conclusions from the POPLU experiment relating to Posiva's reference deposition tunnel plug and the development of the alternative wedge plug.

The information presented in this chapter focuses on a summary of the performance of the experiment. In addition to the further information on the design basis and construction of the POPLU experiment provided in other reports and references therein as indicated above, further details on the POPLU experiment are provided in the POPLU experiment summary report (Holt and Koho, 2016).

Modelling of the long-term behaviour of the wedge-shaped deposition tunnel plug was not part of the DOPAS Project.

[8] As discussed later in this section, this report includes information on the first phase of pressurisation. Further reporting on the response to pressurisation will be included in the POPLU experiment summary report (Holt and Koho, 2016).

## 7.1 Posiva Deposition Tunnel Plug Design Basis

### 7.1.1 Deposition Tunnel Plug Safety Functions

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 6.1.1 (Posiva, 2012b). 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.

Materials that will be used to fill openings (e.g., deposition tunnels, other tunnels and shafts) created during the emplacement of spent fuel disposal containers and buffer are called "sealing structures". The sealing structures of deposition tunnels consist of the backfill and plugs. Plugs will be placed at the entrance of deposition tunnels. These plugs are referred to as "deposition tunnel plugs" or "deposition tunnel end plugs" (the term "deposition tunnel plug" is used in this report for consistency with the terminology used for the DOMPLU experiment).

The safety functions of the sealing structures (backfill and plug) according to Posiva (2012d) are to:

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

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

### 7.1.2 Deposition Tunnel Plug Design

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 6.1.2 and Figure 6.2) (Posiva, 2012b). However, there will be two variations for deposition tunnel heights depending on the origin of the spent fuel being disposed of in the Posiva repository, which results in two different plug heights being used.

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 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 EDZ (Haaramo and Lehtonen, 2009). In the POPLU design (Figure 7.1), the wedge-shaped concrete structure is cast directly adjacent to a filter layer in front of a concrete tunnel back wall. The concrete back wall was considered to simplify installation. In the real repository, bentonite tunnel backfill will be present behind the plug. The plug contains grouting tubes and bentonite circular tapes at the rock-concrete interface to ensure watertightness. Stainless steel reinforcement is used in the concrete structure. The conceptual design of the wedge plug that is being tested in POPLU and is illustrated in Figure 7.1.

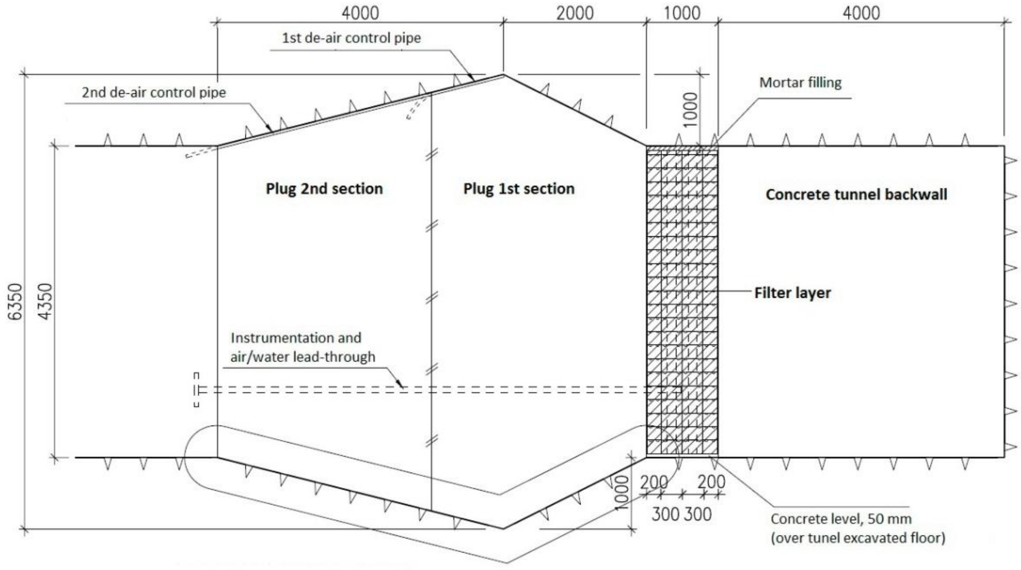



**Figure 7.1**: Schematic illustration of the Posiva's wedge-shaped plug being tested in POPLU (Holt, 2014).

### 7.1.3 Key Design Specifications in the POPLU Experiment Design Basis

The key design specifications contained within the design basis and which are directly tested through measurement of the results of the POPLU experiment or during materials development are presented in Table 7.1. More information on the design basis can be found in White *et al.* (2014). The full design basis contains a much greater number of requirements; only the most significant design specifications, including those related to the design and monitoring work discussed in this report, have been listed here and are considered in this summary report (see Section 3.5 for context and justification for the selection of "key" design specifications). Evaluation of the performance of the POPLU experiment compared to the design basis is an on-going activity within Posiva. Note that some of the more general reference design requirements and specifications as described in Posiva's VAHA system (and within White *et al.* (2014)) and which had no impact from POPLU are excluded from the analysis of this report, specifically Table 7.1 and Table 7.4. Yet these are included within the POPLU summary report (Holt and Koho, 2016).

**Table 7.1:** Key design specifications tested through measurement of the results of the POPLU experiment or during materials development as part of the experiment. Note that this table excludes some of the more general reference design

requirements and specifications as described in Posiva's VAHA system, yet these are included within the POPLU summary report (Holt and Koho, 2016).

| ID | Design Specification | Justification | Compliance Approach |
|---|---|---|---|
| POPDS01 | The cementitious materials that are used in plugs shall have a calcium to silica mass ratio less than 1:1. | 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. Potential reactions include the loss of swelling capacity, and changes in porosity, mineralogical composition, or sorption capacity. To minimise these reactions, low-pH concrete must be used. Posiva expects that the pH of concrete leachate shall be <11 at the age of 91 days when tested in ONKALO simulated deep groundwater.<br>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 further requirement on the calcium to silica mass ratio. | Quality control sampling of the concrete mix.<br>In addition, part of the compliance approach is the testing of concrete mixes to demonstrate that the pH of leachate is <11 at 91 days in ONKALO simulated deep groundwater. This includes testing of mixes in the laboratory during material development and taking quality control samples from plug castings at various ages. |
| POPDS02 | The compressive strength of the concrete shall be greater than 50 MPa at 91 days. | The requirement on compressive strength is introduced to ensure the mechanical and hydraulic integrity of the plug under the loads to which it will be subjected. The value of 50 MPa is based on numerical modelling, and considers a pressure load of at least 7.5 MPa including the ambient hydrostatic pressure. Provision of a concrete with a compressive strength of 50 MPa also contributes to ensuring that the plug shall have a service life of 100 years. | Accurate design and modelling, with validation of resistance to 7.5 MPa by pressurisation of the plug and performance evaluation from the monitoring system.<br>Quality control samples from plug castings at various ages to verify strength.<br>Monitoring of strain and total pressure within concrete plug, as an indicator of potential cracks occurring during pressurisation. |

| ID | Design Specification | Justification | Compliance Approach |
|---|---|---|---|
| POPDS03 | Fresh concrete workability 560 – 640 mm of slump flow. | The design of the POPLU experiment requires that the concrete wedge is emplaced by pumping and filling of the crown section of the wedge without vibration. This ensures the watertightness of the plug (hydraulic conductivity and permeability, especially at interface areas and relatively dense reinforcement).<br>Slump flow is considered by Posiva to be a particularly significant requirement for the concrete wedge design owing to the massive nature of the wedge in the POPLU design which will need high flowability, or self-compaction, to achieve a greater length of the plug without vibration. It has therefore been retained in the list of key design specifications for POPLU. Slump flow is also a design specification considered in other experiments but is not included in the tables of key design specifications as standard concrete specifications are applied in the other experiments and have not been highlighted in this summary report. | Laboratory testing to develop mix proportions and validate slump flow.<br>Quality control testing at the concrete factory and on site, prior to pumping/placement to wedge formwork. |
| POPDS04 | 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.<br>Monitoring of the curing temperature using sensors embedded in the concrete wedge. |
| POPDS05 | 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 watertightness of the plug.<br>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.<br>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. |

| ID | Design Specification | Justification | Compliance Approach |
|---|---|---|---|
| POPDS06 | The hydraulic conductivity of the concrete mass shall be <1x10$^{-11}$ m/s. | The concrete must be water tight after installation to ensure the preservation of the buffer and backfill material in the deposition tunnels and deposition holes. This reduces the risk of radionuclide transport. Watertightness is defined in terms of a hydraulic conductivity for the concrete. | Leakage monitoring with pressurisation simulating the design life. Maximum leakage rate 0.1 litres/min (6 litres/hour) through the plug and interface. Quality control samples of the concrete, water tightness values under 50 mm. |
| POPDS07 | The organics content in the plug shall be lower than 1 wt-%. | The POPLU experiment is undertaken in the ONKALO facility, which will form a part of the future Olkiluoto repository. Therefore, no materials can be introduced into the experiment that may affect the safety of the repository. Future plugs in the repository will also have similar requirements concerning organic material. Organics could affect repository performance by complexing with radionuclides and accelerating radionuclide transport. The quantity of organic material in the repository is therefore limited. | Foreign material review of all material data sheets prior to approval for use (i.e. concrete raw materials). |
| POPDS08 | The total sulphur content in the plug shall be less than 1 wt-%, with sulphides making, at most, half of this. | The POPLU experiment is undertaken in the ONKALO facility, which will form a part of the future Olkiluoto repository. Therefore, no materials can be introduced into the experiment that may affect the safety of the repository. Sulphur, and in particular sulphides, could react chemically with bentonite, which may affect its physical and chemical properties. The quantity of sulphur in the repository is therefore limited. | Foreign material review of all material data sheets prior to approval for use (i.e. concrete raw materials). |
| POPDS09 | The pressure against the plug shall be minimal before the concrete has cured and gained sufficient strength. | If pressure is applied before the plug has gained sufficient strength, it could be damaged and thus not maintain its design function. | Monitoring of strain and total pressure within concrete plug during casting and initial phase. Monitoring total pressure on formwork during casting. |
| POPDS10 | The plug location shall be selected so as to not have hydraulically conductive fractures intersecting the entire length of the plug. The plug location shall not be intersected by brittle deformation zones. | The concrete must be water tight after installation to ensure the preservation of the buffer and backfill material in the deposition tunnels and deposition holes. This reduces the risk of radionuclide transport. | RSC for plug location siting.<br>Monitoring of water pressure and water quality in near field boreholes during pressurisation. |

| ID | Design Specification | Justification | Compliance Approach |
|---|---|---|---|
| POPDS11 | Wedge design allows for movement of the plug due to pressurisation. | Mechanical modeling of the structural design shows expected displacement of 1-2 mm at a pressure of 10 MPa. | Monitoring of displacement within concrete plug, during pressurisation. Validation of modelling. |

## 7.2 Summary of POPLU Experiment

### 7.2.1 Objectives of POPLU

As noted above, the POPLU experiment considers an alternative to the reference plug design. 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 depending on host rock conditions. Further information on the POPLU conceptual design and design basis is presented in White and Doudou (2016) and Holt and Koho (2016).

The POPLU demonstration is implemented to fulfil the YJH-2012 (Posiva, 2012c) 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.

### 7.2.2 Summary of POPLU Design and Construction

The design and construction of POPLU included the following activities (see White and Doudou (2016); Holt and Koho (2016), and Holt and Dunder (2014) for more details):

- Materials development and testing of the proposed concrete mix for the low-pH self-levelling concrete wedge, the concrete grouting mix, the bentonite tapes and the filter.
- Structural design work including mechanical and hydraulic modelling of the expected plug performance and in support of the development of the steel reinforcement placed with the concrete wedge.
- Siting and excavation of the POPLU experiment niche, including application of the rock suitability classification (RSC) methodology, and the development and application of a wedging and grinding technique for excavation of the plug slot.
- Installation of the POPLU experiment components.

These activities are briefly described below. Further information on the design and construction is included in DOPAS (2016b) and the references therein.

***Materials Development and Testing: Including Compliance with Requirements POPDS01, POPDS07 and POPDS08***

The Posiva reference low-pH concrete has some similarities to the B200 mix used in the DOMPLU experiment, which was one of the starting point references for the Posiva mix design (Vogt *et al*., 2009). For the POPLU experiment, a different type of superplasticiser was needed. Two different concrete mixes were selected for four large-scale mock-up tests prior to POPLU casting, with the difference being a binary or ternary composition of the binder material. The large-scale preliminary testing included a surface mock-up in the shape of the plug slot (used for the first and third tests) and an underground cubic box (used for the second test), in addition to a concrete cap against the rock for a grouting trial (fourth test) (Holt, 2014).

The concrete mix selected for use in the POPLU experiment was a ternary mix with a binder composition of 38% cement, 32% silica fume and 30% fly ash (Holt, 2014). The incorporation of the silica fume and fly ash (with suitable chemical composition) contributes towards compliance with requirement POPDS01. The mock-up tests identified several improvements to the concrete mix and the casting procedure, for example, the use of 16-mm, rather than 32-mm aggregate in the top and bottom of the plug (i.e., where the reinforcement is most extensive). The concrete mix includes low quantities of organics and sulphur for consistency with requirements POPDS07 and POPDS08 (Holt, 2014).

The injection grout used in the POPLU experiment was based on a mix previously developed, tested and further modified for field use by Posiva (Kronlöf, 2005; Raivio and Hansen, 2007; and Ranta-Korpi *et al*., 2007). The cement-based mortar has a low pH. The amount of silica fume in the grouting mortar is high and therefore a slurry superplasticiser was used to aid workability, instead of a powder superplasticiser. Accelerating agents are not included in the mix because they restrict the penetrability of the grout. The grout mix was tested in a mock-up which verified the readiness of the mix for use in the POPLU experiment.

Six products/suppliers were evaluated to select the most appropriate material for the bentonite tape. This included testing of the swelling in the laboratory in various groundwater conditions. The chosen brand (Super Stop) had the greatest swelling after one day. This brand was also chosen as it had the highest amount of bentonite within the tape compared to the other products, and thus the lowest amount of foreign materials.

The filter block materials were manufactured by a contractor using lightweight porous aggregate and a low-pH paste having binder proportions similar to the plug binary concrete mix design (40% silica fume and 60% cement as the binder, and a maximum binder content of 200 $kg/m^3$). Dimensions were determined by mould availability in the factory.

***Structural Design Work: Including Compliance with Requirement POPDS02***

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, including the reinforcement required to meet the 50 MPa compressive strength requirement specified in POPDS02 (see discussion in Holt and Koho (2016), DOPAS (2016b), Holt and Dunder (2014), and DOPAS (2016c)).

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 watertightness 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 (2016c) and Rautioaho (2016)).

***Siting and Excavation: Including Compliance with Requirement POPDS10***

The proposed location of the POPLU experiment was adjacent to existing research tunnels, referred to as Demonstration Tunnel 1 and Demonstration Tunnel 2. The POPLU experiment required the excavation of two new tunnels excavated separately from DOPAS Project, Demonstration Tunnel 3 and Demonstration Tunnel 4, which would contain, respectively, the monitoring equipment and the plug itself.

To verify the suitability of the plug demonstration tunnels and to select the location for the plug within the tunnels, the RSC methodology developed by Posiva Oy was applied (Kosunen, 2014). The suitability of the rock in the POPLU experiment area was assessed three times using the RSC. The first classification was based on information gained from pilot holes (one drilled for each planned tunnel location) and was used to select the approximate chainage 11-17 m of Demonstration Tunnel 4 as the primary candidate for the plug location. The second classification was carried out after the excavation of the Demonstration Tunnel 4 had proceeded past the suggested plug location, and based on the tunnel observations, the suggested location was verified to be suitable for hosting a plug (Kosunen, 2014). The third RSC application was done for confirmation after the slot excavation for validation of the previous two methods and for demonstration of compliance with design specification POPDS10.

The standard set of RSC investigations were applied during the siting of the POPLU experiment. This comprised geological logging of the drill core and sampling for rock mechanical tests, optical and acoustic drill hole imaging, as well as a set of geophysical surveys and hydraulic measurements. During the geological logging, several parameters describing lithology, foliation, fracturing, deformation zones and weathering were recorded, and the resulting data were then utilised in the preliminary interpretation of data from the geophysical surveys and the hydraulic measurements (for example, flow log data). The RSC data were then used to generate a detailed-scale model of the volume. In this case, two models were generated. In the first, the modelled volume included Demonstration Tunnels 3 and 4. The second model focused on the plug slot area.

The selected method for the plug slot production was a combination of drilling, wedging and grinding. These combined methods were 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 the other DOPAS Project experiments (i.e., hydraulic wedge splitting and pressure disintegration techniques as used in EPSP, and wire sawing as used in the DOMPLU experiment) to be able to compare and contrast the methods.

***Experiment Installation***

All installed components of the plug system in the POPLU experiment are illustrated in Figure 7.1. Some components of the experiment were installed separately while others were installed in parallel with assembly of the components progressing vertically. The stages in installation were as follows (further information on the experiment installation is provided in DOPAS (2016b) and Holt and Koho (2016)).:

- Rock Support: The first step when proceeding with construction of the actual plug was to build a protective shelter and scaffolding against falling rock within the plug slot area of Demonstration Tunnel 4.
- Rock and Concrete Lead-throughs: Lead-through pipes were delivered in three sections and were welded together underground, with all stages being subject to quality control testing. The concrete lead-through was wrapped with bentonite tape to aid watertightness through the plug.
- Formwork: The formwork used a bracing frame, which eliminated the need to drill attachments into the rock directly adjacent to the plug slot.
- Tunnel Back wall: The back wall was constructed using the same low-pH concrete as used for the concrete wedge but without reinforcement, allowing practising of the installation processes prior to construction of the wedge itself.
- Filter Layer: The lightweight aggregate blocks were assembled in a wall using low-pH mortar, with the final blocks being hand-sawn to fit the tunnel dimensions. Some lightweight aggregate was used for filling gaps and protecting lead-through instrumentation.
- Concrete Wedge: The concrete wedge was poured in two sections following the installation of the reinforcement (in three phases), the grouting tubes and bentonite tapes, and the concrete lead-through pipe.
- Grouting of the Wedge-rock Interface: Grouting was done over a two week period, three months after concrete hardening. Three of the six grouting lines were flushed with water after grouting to allow for future re-grouting if needed.
- Monitoring systems: Instrumentation was installed during the various phases above, including performance monitoring of the near-field rock (between Demonstration Tunnels 3 and 4, and in the back wall), filter layer and concrete plug. The data collection system was running through all phases of these installations. In addition to information on the monitoring system in DOPAS (2016b) and Holt and Koho (2016), further information, including the monitoring test plan, is provided in Hakola *et al*. (2014).

### 7.3 Learning Related to Construction and Operational Issues: Including Compliance with POPDS07, POPDS08 and POPDS10

The construction process yielded many valuable lessons. Some of the key points are summarised here:

- The RSC methodology was found to be suitable for evaluating the rock quality and establishing the plug slot location. The RSC was validated after slot manufacturing by iteration of the process and confirmed compliance with design specification POPDS10.
- The safety precautions planned by contractors offering to use wire sawing for the slot excavation did not pass a health and safety review by Posiva. The safety risks were considered too high with respect to the potential for rock fall during the slot excavation, especially from the ceiling section. The method for slot excavation was changed to a drill, wedge and grind method. This alternative method proved to be suitable,

especially regarding safety and with respect to the extent of disturbance of the rock caused by the drilling and the potential for this drilling to create additional groundwater flow paths. The method was predictable for cost and time scheduling. The evenness of the slot rock surface was not expected to be as smooth as expected from wire sawing, but surface evenness was not a criterion for the wedge design based on the structural expectations to maintain the plug dimensions with reinforcement steel and low shrinkage of the wedge concrete.

- It is important to have a clear definition and justification for the requirements set on material and structural parameters. During POPLU, the tolerance requirements for the slot dimensions were stricter than needed according to the structural designers, yet the slot dimensions after excavation needed to be repeatedly verified and then additional grinding performed to get the slot size within specifications. This caused schedule delays and thus subsequent budget overruns to other parts of the project.
- The rock support system in the slot area was successfully used and would be needed in the future for worker safety. The methodologies for installing the reinforcement cages within the slot area were valuable, and these cages also serve as temporary rock support.
- The foreign material acceptance review procedure was valuable for ensuring the performance of the future repository environment. Material data specifications were provided and reviewed before materials were accepted for use in ONKALO. The materials of POPLU were specified if they were for experimental purposes or would be used in actual repository operational plugs. The assessment allowed for greater understanding of quality control procedures and material procurement details, and confirmed compliance with design specifications POPDS07 and POPDS08.
- The bentonite tape and grouting tubes were easy to install around the circumference of the slot prior to reinforcement installation. They were attached with small nails to the rock, which should be included in the foreign material acceptance review.
- The formwork used for bracing of the back wall and the two plug sections was massive. It was designed to account for a full-hydraulic pressure of self-compacting concrete during pumping. There was a high level of safety factored into the design, which could be evaluated in the future based on the results of formwork pressure during concrete casting. The formwork system was good in that it did not create additional holes to the rock near the plug slot, rather, it relied on a bracing frame closer to the central tunnel together with extendable hydraulic jacks.
- The concrete mix was suitable for the plug construction, also based on the earlier laboratory development, three mock-up tests and tunnel back wall casting. The low-pH material could be easily mixed, transported and pumped into place. The quality control methods were well-planned and sufficient.
- The instrumentation system was for experimental purposes and would not be as extensive within operational plugs in the repository. But there are many lessons learned regarding installation that can be helpful for other EBS experiments or forms of repository monitoring. The installation of monitoring systems inside the plug sections and slot area was challenging. Workers needed to install sensors in very confined spaces, sometimes working simultaneously with other contractors as well as working between reinforcement bars and in narrow gap openings to the rock. Attachments for the monitoring system need to be well-planned and reviewed for foreign materials. The installation of sheltering tubes and wire connections for the monitoring system required

high amounts of planning and are not standardised products for watertightness. There needed to be good coordination with the construction team regarding the work phases and timing when instrumentation experts would have access. Often, the instrumentation could only be installed during concise, periodic shifts, and not in a continuous longer period, due to readiness of the surrounding materials. In some cases, work progress by other contractors required sensors to be removed and later re-mounted. There should be a good exchange of work plans and drawings so as to avoid conflicts or errors in monitoring system design and emplacement.

After construction of the plug, the contractors commented that they would have preferred to have had more detailed method descriptions and designs, so that they could have more accurately planned and implemented the work. However, contractors also noted that the documentation should have some level of flexibility and allowed deviations that could be implemented after suggestions, review and approval. In this way they can bring their experience and expertise to the project, which can result in a safer structure and/or more economic implementation.

### 7.4 Evaluation of Performance of POPLU Components Prior to Pressurisation

In this section the performance at the time of installation of the POPLU experiment with respect to the design specifications listed in Table 7.1 is evaluated. This is focussed on the monitoring of concrete properties including leachate pH, compressive strength and curing temperature, which contributes to the compliance assessment for POPDS01 (leachate pH), POPDS02 (compressive strength), POPDS03 (slump flow) and POPDS04 (curing temperature).

The system used to measure and monitor the installation of POPLU is described in DOPAS (2016b) and references therein. Holt and Koho (2016) provides a more extensive discussion of the performance of the POPLU experiment.

During construction and concrete delivery, 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. The average results of these tests are presented in Table 7.2 for Plug Section One and Two, for both mixtures with 16 mm and 32 mm maximum aggregate size. In Table 7.2, the reference values from the laboratory concrete trials are given (from Holt, 2014). The value for the pH of the concrete leachate is consistent with design specification POPDS01 (Table 7.1). The value for the compressive strength of the concrete is consistent with design specification POPDS02 (Table 7.1). The value for the slump flow of the concrete is consistent with design specification POPDS03 (Table 7.1). These results confirm that POPLU implementation had a durable concrete with suitable rheology/flow characteristics, which is self-compacting in nature. These results support the possibility that it would be feasible to construct the plug in one section rather than two without vibration (thus the concrete can flow to fill a mould of greater depth).

After concrete placement and during the first days, the most critical factor for the structural design and plug performance was the temperature development of the concrete associated with cement curing. The mix and structural design specified that the material should stay below 60°C (POPDS04, Table 7.1), and the mix based on laboratory experiments and modelling was predicted to be below 50°C. The maximum curing temperature that occurred was approximately 42°C (Figure 7.2). The two peaks shown in Figure 7.2 correspond to the time of the two different wedge section castings. The temperature monitoring results provide evidence that it would be feasible to construct the plug in one section rather than two without excessive heat development.

**Table 7.2**: Fresh and hardened concrete properties of both plug casting sections.

| Parameter | Summary of Concrete Properties | | | | | |
|---|---|---|---|---|---|---|
| | POPLU Target | Laboratory Design Ternary Mixture | Wedge: Section 1 | | Wedge: Section 2 | |
| | | | 16 mm | 32 mm | 16 mm | 32 mm |
| Average slump flow (mm) | 600 | 290 | 610 | 611 | 607 | 598 |
| Range (±) in slump flow (mm) | 40 | NA | 40 | 70 | 40 | 90 |
| Compressive strength at 91 days (MPa) | >50 | 79.5 | 77.7 | 92.3 | 79.4 | 81.2 |
| Watertightness at 91 days (mm) | ≤50 | 5.0 | 3.0 | 3.3 | 1.0 | 1.0 |
| Leachate pH at 28 days in simulated Olkiluoto groundwater | NA | NA | 10.9 | 10.9 | 10.9 | 11 |
| Leachate pH at 91 days in simulated Olkiluoto groundwater | <11 | 10.3 | 10.9 | 10.9 | 10.8 | 10.8 |
| Concrete volume ($m^3$) | NA | NA | 36 | 60 | 44 | 36 |

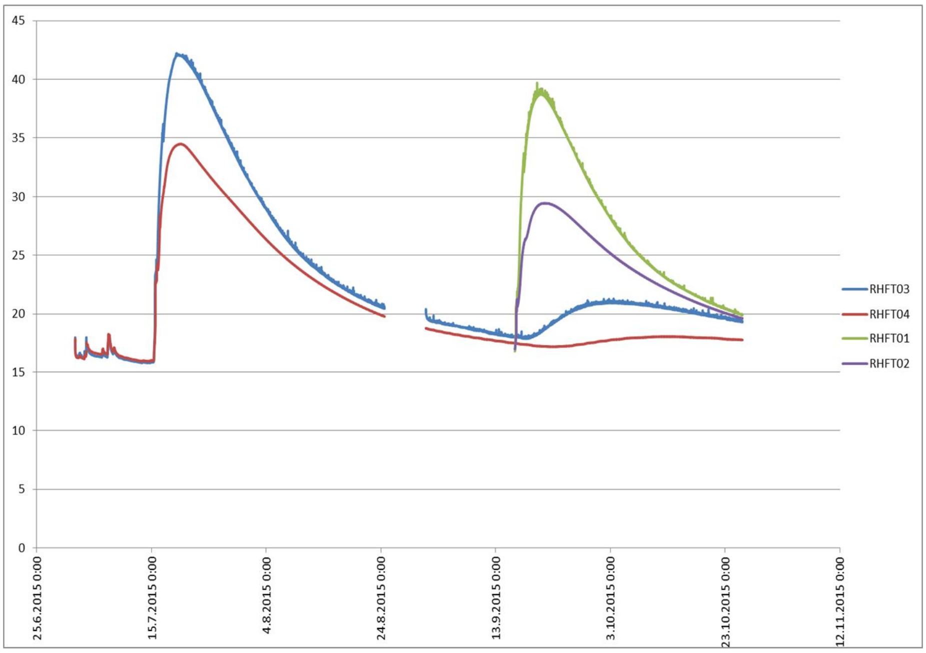



**Figure 7.2**: Temperature development (°C) of concrete following concrete wedge pouring, measured from the centre of each wedge section.

## 7.5 Evaluation of Performance of POPLU Components during Pressurisation

The assessment of POPLU performance has relied on interpretation of the following parameters:

- The monitoring system comprised of approximately 130 sensors within the plug and filter layer (measuring temperature, relative humidity, strain, displacement, total pressure, pore pressure).

- Measurement and visual assessment of water leakage from the plug and near field, including assessment of tracer from the pressurisation water.
- Near field assessment of water pressure and water quality in boreholes and from fractures, including measurements in Demonstration Tunnels 1, 3 and 4, central tunnel and 10 boreholes.
- Two rock extensometers evaluating stresses between Demonstration Tunnel 3 and 4 (perpendicular to the slot and plug area).

This monitoring will be used to assess the performance of the POPLU experiment with respect to the design specifications listed in Table 7.1:

- Monitoring of temperature was used to assess compliance with POPDS04 (see Section 7.4).
- Monitoring of relative humidity will be used for general understanding of the performance of the plug.
- Monitoring of strain and displacement will be used to assess compliance with POPDS11.
- Monitoring of total pressure and pore pressure will be used to assess compliance with POPDS02 and POPDS09.
- Monitoring of water leakage will be used to assess compliance with POPDS05 and POPDS06.
- Monitoring of water pressure and water quality in boreholes will be used for general understanding of the performance of the plug.
- Monitoring of rock strain, which contributes to the understanding of the rock response to plug emplacement and is not linked to any performance criteria.
- Monitoring of rock stresses will be used for general understanding of the performance of the plug.

Pressurisation of the POPLU experiment commenced in January 2016. This report contains monitoring data acquired up to and including 29 February 2016, by which time an initial pressurisation phase had been undertaken in which the experiment had been pressurised to 1 MPa. By this time, no displacement, strains or temperature changes in the plug sensors in response to the pressurisation had been detected. Water movement through the POPLU plug was indicated by relative humidity measurements but these data are not yet quality assured, and are therefore not included in this report. There has also not been a significant increase in water pressures measured in the surrounding boreholes, or additional visual leakage detection in the near-field monitoring locations. Therefore, the discussion of performance of the POPLU experiment during pressurisation focuses on the monitoring of leakage rates in compliance with POPDS05 and POPDS06. Further performance evaluation at pressures up to 4 MPa are included in the POPLU summary report (Holt and Koho, 2016).

Pressurisation commenced with the filling of the filter with water, which took approximately seven days. Water filling was undertaken slowly to allow for air escape from the filter layer. The total volume of water used to fill the filter was 13 $m^3$. During this period, the total pressure within the filter layer remained below 100 kPa. Figure 7.4 shows the response of the total pressure sensors in the filter layer during the water filling.

Once the filter was filled with water, pressurisation could commence. The originally plan for the pressurisation sequence is shown in Figure 7.3 (the inset to Figure 7.3 shows the early stage of pressurisation in more detail to highlight the water filling sequence also). In the early stage of pressurisation, the water pressure in the filter was increased to 1 MPa in two steps.

Within 24 hours of the pressure in the filter reaching 1 MPa, leakage water was detected from the contact grouting area on the sides of the plug (Figure 7.5). Figure 7.6 illustrates the levels of pressurisation and average water leakage detected. The leakage amounts detected visually and by quantitative measurements decreased by over 40% within a week. This is assumed to be the result of activation of the bentonite tape leading to inhibition of water flow.

During the initial measurements of total leakage, approximately a quarter of the leakage was along the wiring and sheltering tubes of the monitoring system, while the remainder was within the interface (plug-rock) areas. The majority of the leakage occurred through both the interface and the slot EDZ that was not sufficiently sealed by contact grouting. The monitoring system leakage is an artefact of the experimental arrangement, and not a structural (or watertightness) fault of the plug design itself.

An example of the total pressure sensor response is shown in Figure 7.7, with the change of total pressure in the plug area during pressurisation. From this graph, it can be seen that some of the sensors are registering pressure levels in the range of 0.2 to 0.9 MPa, when the pressure level in the filter layer was 1 MPa. This result indicates that that the concrete wedge-rock interface was not watertight and that the contact grouting was insufficient.

After 14 days (4 February 2016), the pressure was increased to 1.2 MPa. This led to an initial increase in water leakage, as shown in Figure 7.6, followed by a fall-off in the leakage rate prior to the next incremental step in pressure implemented on 11 February 2016. The data demonstrates the ability of the plug to diminish leakage with time, potentially due to the impact of the bentonite tapes.

Based on the results achieved to date, it was decided to re-grout the plug interface with an improved grout mix and methodology. This activity was planned to be undertaken after the freeze date for this report[9]. It is expected that the pressurisation and performance evaluation will be undertaken with pressures up to 4 MPa, both prior to, and after, the re-grouting is completed, with results (up to pressures of 4 MPa) being reported in the POPLU summary report (Holt and Koho, 2016), and results following grouting to be reported by Posiva when available.

During slot excavation, rock extensometers were used to evaluate any stresses or displacements in the rock between Demonstration Tunnel 3 and 4, perpendicular to the slot area. These sensors were also used for the evaluation of contact grouting and during the pressurisation phase of the experiment to monitor the plug response to the pressurisation. An example of rock displacement monitoring during pressurisation is shown in Figure 7.8.

Based on the results obtained up to the end of February 2016, the concrete plug itself is performing satisfactorily. Despite the greater than expected leakage during the early stages of pressurisation, the detected leakage amounts are still below the target criterion in the pressurisation plan of 0.1 litres/minute (6 litres/hour) prior to increasing the pressure to the next step. However, the contact grouting for sealing of the EDZ in the slot area needs to be improved.

[9] Such work might provide information on mitigating actions that could be undertaken in a repository, but it is too early to determine if this is the case.

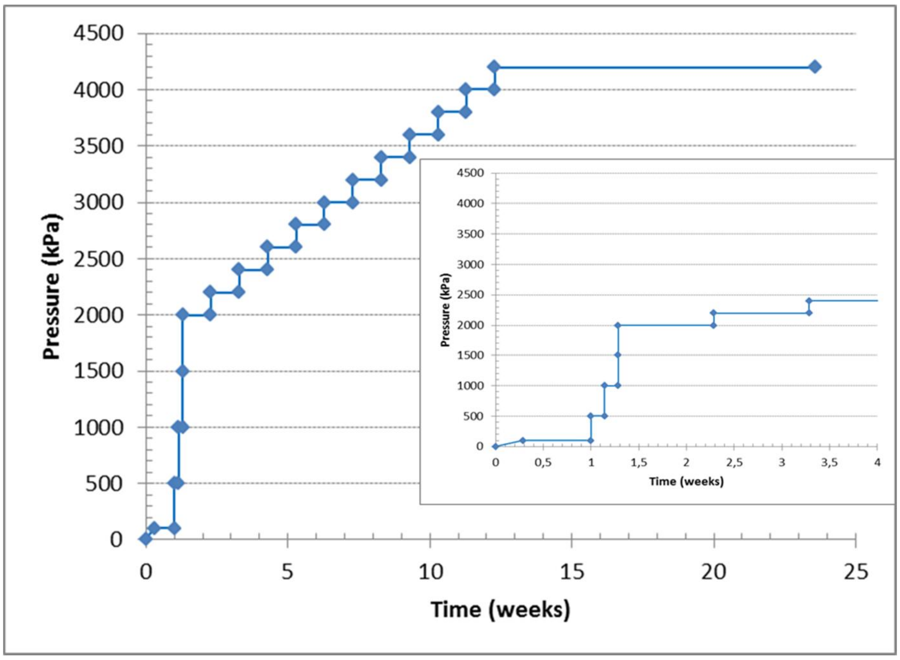



**Figure 7.3**: Originally planned water filling and pressurisation sequence.

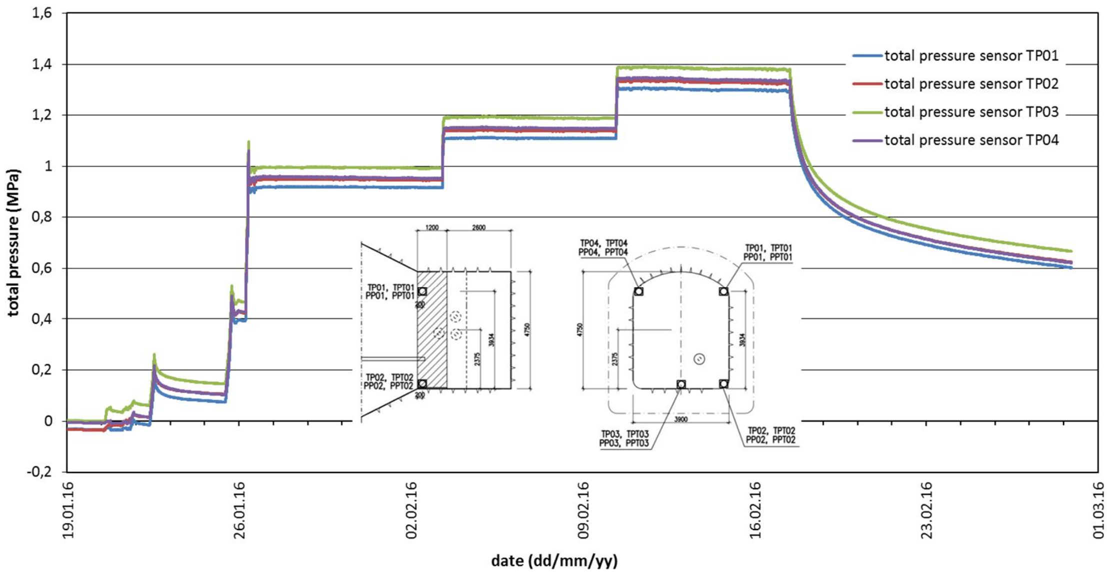



**Figure 7.4**: Example response of total pressure sensors in the filter during water filling and pressurisation up to 1.4 MPa.

**Figure 7.5**: Visual appearance of minor plug leakage from the interface areas at top and sides of plug.

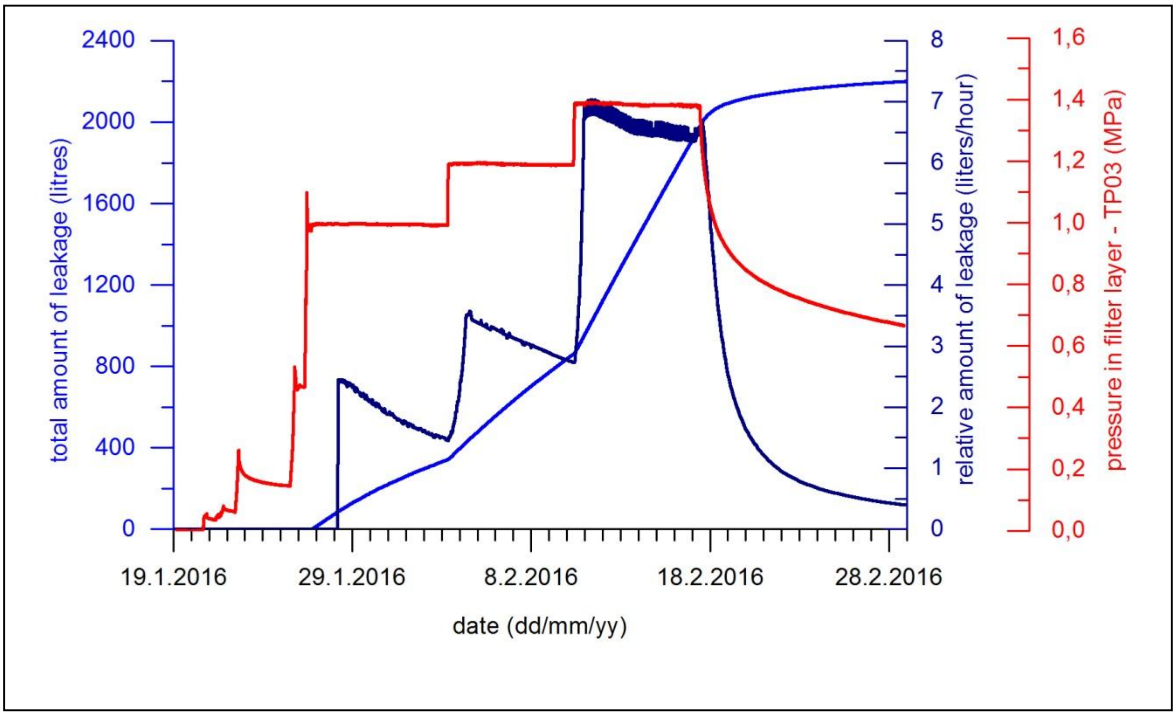



**Figure 7.6**: Plot of cumulative leakage, leakage rate and pressure in the filter layer (as measured by total pressure sensor TP03) during the initial phase of pressurisation of the POPLU experiment.

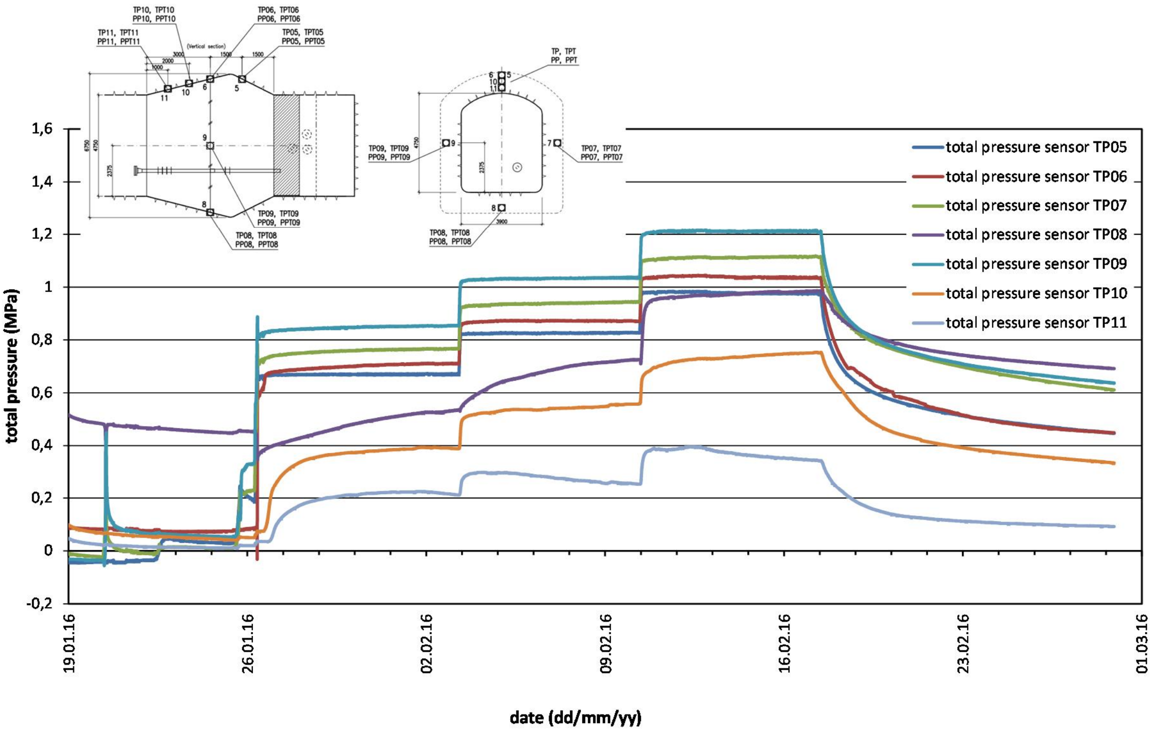



**Figure 7.7**: Example response of total pressure sensors in plug area after start of pressurisation (pressure level in filter at 1.4 MPa).

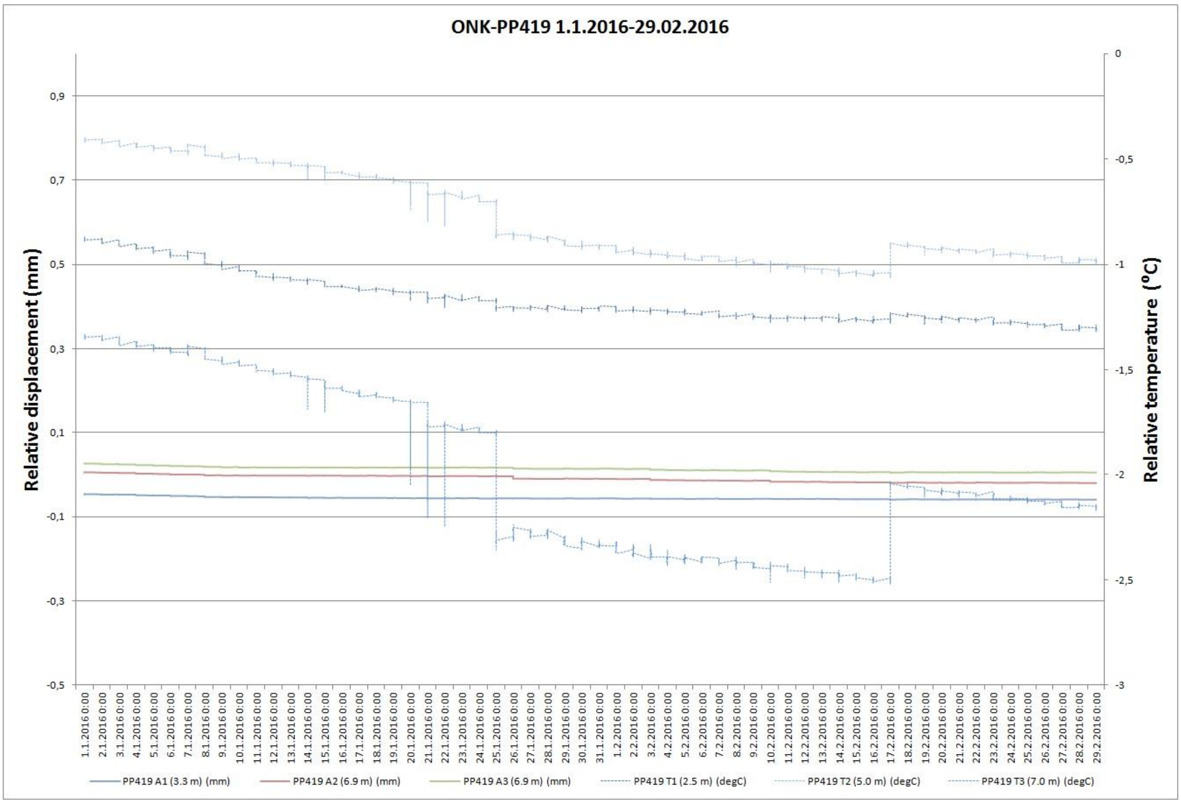



**Figure 7.8**: Example measurement of rock displacements during pressurisation.

## 7.6 Evaluation of the POPLU Experiment Monitoring System

The instrumentation, pressurisation system and leakage detection system components of the monitoring system have performed well. The data collection, transfer and back-up system have also performed well. The system has given reliable information during the construction and casting activities, which have helped in decision making.

For long-term performance of the POPLU experiment, the primary concern with the sensor arrangement within plug section two is the risk of a pathway for water leakage that has been realised. Approximately seven sensors have shown water running along their cabling and/or sheltering tubes at the front face of the plug. The amount of water leakage along the monitoring system is less than the estimated plug interface (rock) leakage in the slot area. The experience leads to lessons about the best selection for materials and sheltering, including fasteners and other components. The instrumentation system was designed with redundancies and variable configurations, so as to learn which solutions for the harsh environment of repository monitoring are the best.

A parameter-by-parameter evaluation of the monitoring system, is provided in Table 7.3. Further information is available in Holt and Koho (2016).

**Table 7.3**: Evaluation of the POPLU experiment monitoring system. Further information is available in Holt and Koho (2016).

| Sensor | Parameter(s) | Evaluation |
|---|---|---|
| K30-2-506 K-type<br><br>INOR TCA-M10-MT1 | Temperature in the concrete plug and concrete back wall | Temperature measurement was mainly used to follow temperatures during and after casting where the sensors performed consistently. Inor type sensors showed incompatibility with data loggers. A new logging solution had to be installed. Cause for incompatibility is still unknown.<br><br>Temperature measurement suffered from distortions before final installation, when all shielding was connected properly. There is still noise superimposed on the measurements. Its cause is not yet identified. |
| Fuktcom, FE102<br><br>Aitemin, SHT75 V3 | Relative humidity in the concrete plug and concrete back wall | Two of three Aitemin sensors failed before or during pressurisation. Three of four Fuktcom sensors show constantly 100% RH, partly interrupted by failure signals.<br><br>Either the sealing of some of the sensors has failed or the sensor itself failed in contact with pressurised concrete pore water (RH close to 100%). Some of the measurement readings include distortion. |

| Sensor | Parameter(s) | Evaluation |
| --- | --- | --- |
| Kyowa, KFG-5-120-C1-11L1M2R | Strain in the concrete plug, measured with strain gages attached to rebars of 100 cm length. | With increasing time of pressurisation, more and more strain gauges showed conspicuous readings or failed. For some of the sensors, the sealing of the sensor connections to the sheltering has failed and readings include distortion.<br>Although tested for pressures up to 100 bars and for 48 hours in a pressure vessel prior to installation, the sealing concept can be considered as not sufficient for the harsh environment inside the pressurised concrete. |
| RDP Electronis LTD, SSD500/1425<br>Kyowa, BCD-5B | Displacement of the plug is measured relative to the surrounding rock. LVDT-sensors (SSD500/1425) measure displacement from the back part of the plug and Kyowa “Omega” sensors from the surface of the plug. | Generally, all sensors are performing well. Little distortion is superimposed to the measurements, caused by strong electromagnetic fields of unknown source. |
| Geokon, 4800-1X-10 | Total pressure in the filter layer and in the interface between concrete plug and rock surface | Sensors are generally performing well, showing pressure changes in the filter layer and plug/rock interface accurately. For the sensors in the interface, the pressure values cannot be considered as absolute pressure values due to the stiff embedment of the sensors, which are meant to be used in soil, or other non-rigid media. |
| Geokon, 4500SHX-3-10 | Pore pressure in the filter layer and in the interface between concrete plug and rock surface | Sensors are generally performing well, showing pressure changes in the filter layer and plug/rock interface accurately. The sensors demand a pre-filling with water prior installation. Owing to the long period between installation and concrete casting, some of the water might have evaporated and been replaced by air. The sensors showed only accurate reading, after pressurised water contacted the sensor and replaced or dissolved the air inside the sensor. After that, sensor readings are considered to be reliable. |

| Sensor | Parameter(s) | Evaluation |
|---|---|---|
| Drück PTX 1830 + DataTaker | Water pressure in near-field rock,<br>Hydraulic head (mH2O) in nearby boreholes (ONK-PH21, -PH22, -PH23 and ONK-PVA11) | Sensors are performing well. Some distractions in ONK-PH21 between L5 (22,25m) – L9 (2,5m) since 12.4.2016. Might be due to packer pressure increasing. Monitoring the situation weekly.<br>In other boreholes, no indication from POPLU pressurisation. |
| Interfels<br>Multi-Point Borehole Extensometer (MPBX) | Displacement measurements of the rock and temperature inside the borehole | All the sensors are working well.<br>Measurements of the rock displacement during the pressurisation.<br>Measurements of temperature used to correct the errors of the displacement measurements due to thermal expansion of the extensometers. |

Based on the experience of the POPLU experiment to date, the following lessons are noted (further information is available in Holt and Koho (2016)):

- The choice of sensors and the data acquisition must be considered for the harsh repository working environment. In addition to climatic and pressure conditions, there can also be disturbances caused by simultaneous on-going construction and machines (such as blasting from nearby rock excavation) and signal disturbances/noise caused by electromagnetic fields. These items need to be factored in when designing the monitoring systems and evaluating performance data.
- The quality control methods for sensors in laboratory conditions prior to on-site installation needs to be developed for the complexity of the harsh repository environments, especially since post-monitoring sensor retrieval and calibration is often not possible. For example, the strain gauge connects were quality-control tested at 100 bars for 1 hour in laboratory conditions prior to installation to evaluate watertightness and durability. After field installation for POPLU, some of these sensors had questionable readings and the associated data may be disregarded or considered inaccurate in POPLU performance interpretation.
- The complex structure and building process influences the instrumentation support aspects, such as the need for long wires and wire extension possibilities on-site; need for temporary re-location and adjustment of sensor location; re-connection of wiring and data collection boxes so as to avoid damages during construction (i.e., use of temporary sheltering cabinets).
- Access to the plug construction area should be protected from unnecessary visitors and/or contractors as much as possible so as not to disturb the monitoring system during the installation phases.
- The use and functionality of relative humidity sensors in plug environments needs to be evaluated, together with their sheltering system. POPLU has experienced failure with all (3) Aitemin and 1 of 4 Fukton sensors, which is potentially attributed to moisture levels close to the saturation level (100%).
- Both polyvinylidene fluoride (PVDF) and steel tubes have been used for shielding of wires connecting the sensors to the data logging system. The selection of tube type depended on the geometry of the plug and where the wires were being fed. The tube material mechanical properties (like brittleness) may be variable, and thus the connection method between tubes could be influencing the risk of defects and thus leakage.
- There is a lack of compatibility between some sensors and data takers, such as conflict between the Inor thermocouples and data loggers used in POPLU. Such compatibilities should be evaluated before installation or possibly addressed even before equipment procurement.
- There needs to be accurate planning about how to store, transfer and back up the data frequently. The ease of data access is needed for rapid response addressing risk mitigation (i.e., in response to sensor readings and leakage, if the pumps then need to be lowered).

## 7.7 Assessment of Compliance with the Design Basis and Evaluation of the Results with Respect to the Experiment Objectives

In this section, the results from the POPLU experiment are discussed with reference to:

- Compliance with the safety functions presented in Section 7.1.1 is discussed in Section 7.7.1.
- Compliance with the design specifications listed in Table 7.1 of Section 7.1.3 is discussed in Section 7.7.2.
- The preliminary outcomes of the experiment, at the time of writing, with respect to the objectives presented in Section 7.2.1 are discussed in Section 7.7.3.

### 7.7.1 Compliance with the Deposition Tunnel Plug Safety Functions

Conduct and evaluation of the POPLU experiment is not yet complete and all statements regarding compliance with the safety functions reflect the current observations. Additional analysis after experiment dismantling will be used to further assess the compliance to the safety functions.

However, based on the results of the experiment to date, the following can be concluded with regard to the compliance of the POPLU design to the safety functions of Posiva's reference deposition tunnel plug:

- *Contribute to favourable and predictable mechanical, geochemical and hydrogeological conditions for the buffer and canisters*: The deposition tunnel plug has safety functions for maintaining mechanical, geochemical and hydrogeological conditions for the buffer and canister. This is achieved by ensuring the concrete deposition tunnel plug is strong, durable and watertight over the 100-year design life while withstanding the hydrostatic and backfill swelling pressure. This has been achieved to date by the materials testing and development programme, and by the results from the initial pressurisation of the experiment.
- *Contribute to the mechanical stability of the rock adjacent to the deposition tunnels*: By withstanding the hydrostatic and backfill swelling pressure, the POPLU plug will also contribute to the mechanical stability of the rock adjacent to the deposition tunnel.

In addition, the plug design should be such that it does not reduce the performance of the backfill. This has been achieved by developing and installing a low-pH concrete wedge.

The compliance of POPLU with the safety functions of mechanical and geochemical expectations is also met by linking the safety functions to more detailed requirements (design specifications). Evaluation of the performance of the POPLU experiment with respect to the design specifications is described in Section 7.7.2.

### 7.7.2 Compliance with Design Specifications on the POPLU Experiment

An evaluation of the compliance of the POPLU experiment with the design specifications listed in Table 7.1 is presented in Table 7.4. The implications are discussed in Section 7.7.3.

**Table 7.4**: Compliance assessment for key design specifications on the POPLU experiment. The feedback to the design basis is discussed further in the text.

| ID | Requirement / Design Specification | Compliance Assessment | Feedback to Design Basis |
|---|---|---|---|
| POPDS01 | The cementitious materials that are used in plugs shall have a calcium to silica mass ratio less than 1:1. | Compliance with this requirement has been met by adopting a ternary concrete mix containing silica fume and fly ash (see 7.2.2). 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 (see Table 7.2). | Specifying a pH for concrete leachate rather than a calcium to silica ratio is still an option under consideration by Posiva. |
| POPDS02 | The compressive strength of the concrete shall be greater than 50 MPa at 91 days. | The compressive strength of concrete mixes tested lay in the range 77.7-92.3 MPa, confirming compliance with this requirement (see Table 7.2). | This requirement appears appropriate to maintain within the design basis. |
| POPDS03 | Fresh concrete workability 560 – 640 mm of slump flow. | Compliance with this requirement was met for all but one batch of concrete, which had a slump flow of 650 mm, i.e. higher than the stated range. Based on early age quality control tests of the mixture, greater than 97% of the concrete batches met the requirement before emplacement. | This requirement appears appropriate to maintain within the design basis, but there may be a further consideration of the range of acceptable slump flow test results, especially for slump flows that exceed the maximum value stated in the current specification. |
| POPDS04 | The temperature in the concrete wedge shall not exceed 60°C. | The peak temperature measured in the concrete wedge was approximately 42°C (Figure 7.3), confirming compliance with this requirement (see Section 7.4). | This requirement appears appropriate to maintain within the design basis. |
| POPDS05 | Reduce the leakage across the plug to be "as low as possible". | 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 litres/minute (6 litres/hour), thus corrective actions are being taken by re-grouting. | 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. |

| ID | Requirement / Design Specification | Compliance Assessment | Feedback to Design Basis |
|---|---|---|---|
| POPDS06 | The hydraulic conductivity of the concrete mass shall be <1x10$^{-11}$ m/s. | 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. | This requirement appears appropriate to maintain within the design basis based on the concrete mass itself. A 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. |
| POPDS07 | The organics content in the plug shall be lower than 1 wt%. | Compliance with this requirement was demonstrated during materials development and testing, and during the foreign material review of material data sheets and approval for use (i.e. concrete raw materials). | The organics content requirement is appropriate to maintain within the design basis. |
| POPDS08 | The total sulphur content in the plug shall be less than 1 wt%, with sulphides making, at most, half of this. | Compliance with this requirement was demonstrated during materials development and testing, and during the foreign material review of material data sheets and approval for use (i.e. concrete raw materials). | The total sulphur content requirement is appropriate to maintain within the design basis. |
| POPDS09 | The pressure against the plug shall be minimal before the concrete has cured and gained sufficient strength. | Compliance with this requirement was demonstrated during emplacement by a formwork pressure maximum value of 0.9 bars at the middle of the plug height (maximum allowed 1.5 bars). Total and pore pressure monitoring sensors within the plug also showed that the pressure remained under 1 bar within the first 90 days after casting, until grouting. For an operational plug, air pressure or water accumulation from the backfill behind the plug could be released via the filter and concrete lead-through during early ages, so as to prevent pressure accumulations. | This requirement appears appropriate to maintain within the design basis. |

| ID | Requirement / Design Specification | Compliance Assessment | Feedback to Design Basis |
|---|---|---|---|
| POPDS10 | The plug location shall be selected so as to not have hydraulically conductive fractures intersecting the entire length of the plug. The plug location shall not be intersected by brittle deformation zones. | Compliance with this requirement was demonstrated during tunnel and slot siting and post excavation, by application of the RSC methodology. | This requirement appears appropriate to maintain within the design basis. |
| POPDS11 | Wedge design allows for movement of the plug due to pressurisation. | Compliance with this requirement was demonstrated during performance evaluation based on pressurisation to 1.4 MPa. Displacement monitoring sensors attached to the plug can detect movements, though none have been detected as of the data freeze for this report. | This requirement appears appropriate to maintain within the design basis. |

#### 7.7.3 Outcomes of the Experiment with Respect to the Objectives

The objectives of the experiment were presented in Section 7.2.1. The outcomes of the experiment with respect to these objectives are discussed in this sub-section.

*Construct a Full-scale Deposition Tunnel Plug*

Posiva was successful in constructing the full-scale plug, although performance evaluation is still ongoing. There were no accidents or safety infractions during construction. The foreign material review yielded materials that were acceptable for use in the ONKALO facility. Laboratory testing developed suitable concrete mixes for the backwall and plug sections. These mixes were validated by a contractor during mock-up tests prior to installation in the POPLU experiment site. Quality control sampling demonstrated that the low-pH ternary blend concrete used for the concrete wedge was compliant with design requirements related to mechanical and hydrogeological performance. Prior to pouring of the concrete wedge, the formwork was installed and proved effective for self-levelling concrete emplacement at various heights. The concrete reinforcement was successfully installed on-site and integrated with the monitoring system. In addition to the function of minimising the shrinkage of the concrete wedge and preventing crack formation during hydration, the steel reinforcement of the plug sections was also designed to serve the secondary function of rock support within the slot area, which it performed successfully.

The filter layer blocks were of sufficient strength and could be installed behind the concrete wedge sections. During the early stages of pressurising the experiment, the filter blocks have proved sufficient for dispersing the water behind the concrete wedge and for simulating the pressure against the concrete wedge that would be experienced by a deposition tunnel plug during its design life.

The monitoring systems were successfully installed behind and within the concrete wedge and linked to the pressurisation system in the neighbouring tunnel.

The bentonite tape and grouting tubes were successfully installed against the rock surfaces to aid in watertightness of the plug.

The contact grouting mix was not deemed satisfactory owing to the higher than expected water leakage once the pressure in the filter had reached 1 MPa. Therefore, the contact grouting mix and method needs to be re-developed and the concrete wedge re-grouted. This work will be undertaken after the freeze date for this report.

The pressurisation system of pumps, water tubes and lead-throughs was sufficient for generating a load behind the concrete wedge to simulate the operational design life.

More details on the construction of POPLU can be found in DOPAS (2016b) and Holt and Koho (2016).

*Develop the Detailed Structural Design*

The mechanical and hydraulic requirements in the design basis were met by utilising high-strength concrete in the POPLU experiment design. The low-pH ternary blend concrete had high flowability, low curing temperatures, low shrinkage, and low permeability. The material could be placed *in situ* by pumping at various heights to the mould, and demonstrated self-compaction without the need for vibration. The 3-m casting length (when cast in two sections) selected for the POPLU experiment could probably be increased, which would allow for the plug to possibly be cast in one section rather than two.

Casting in one section, rather than two, might allow the structural design to proceed with a lower quantity of reinforcement steel, and is likely to reduce the construction time because there would be no need to construct and install two sets of formwork and reinforcement and undertake two concrete pours. In case of a one-section cast, the temperature difference (gradient) between the tunnel rock walls to the concrete core should be considered, so that it is not too extreme to cause thermal cracking. Options such as temporary wire heating along the rock surface could be explored, so as to minimise the gradient during concrete early age hydration (first days-week). A retractable tube with varying heights of concrete pouring through the formwork should be used to ensure the concrete flows across the whole plug volume (Holt and Koho, 2016).

*Develop the Method for Excavation*

The slot excavation method of drill, wedge and grind produced a suitable slot location for the plug with minimal additional rock fractures or intrusions. The rock smoothness and tolerance was suitable for the structural design of the reinforced concrete wedge. The wire sawing method may still be suitable if the safety precautions are further developed, and this method may be best suited for cases when a smooth rock surface with small tolerances is necessary.

The construction methodologies established by Posiva during the POPLU experiment are suitable for application in operating repositories. These methodologies included, for example, RSC for tunnel and slot siting, design of rock support structures, foreign materials review, oversight of structural and material design, oversight of construction including formwork, reinforcement, concrete and grouting emplacement, and development of the pressurisation procedures.

*Develop Quality Management Practices for the Deposition Tunnel Plug*

The safety review, risk management, change management and quality assessment procedures developed and utilised with the POPLU experiment project allowed decision making and quality documentation to be undertaken efficiently, and underpinned a good work environment without accidents or major realised risks. Frequent project Core Group meetings provided a means for discussion and decision making with the project.

*Develop Instrumentation and Techniques for Monitoring the Performance of Deposition Tunnel Plugs*

The plug monitoring system was functioning as intended at 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 successfully installed and the majority had sufficient water-protective shielding. The sensors were used to evaluate mechanical load transfer, concrete stresses, location of water during pressurisation and temperature development. Companion samples of concrete were used for evaluation of watertightness (hydraulic conductivity), shrinkage, compressive and tensile strength, and pH leachate.

There is a possibility that deposition tunnel plugs will be monitored during repository operation, although this is an open question and, if monitoring were undertaken, the specific types of monitoring that would be employed need to be assessed with respect to any possible impacts on the post-closure safety case. If employed, any systems used to monitor deposition tunnel plug performance should be robust with respect to the complex repository environment and loadings. Sensor technologies and their watertightness need to be improved and verified in realistic conditions prior to implementation.

However, the data obtained from monitoring of the full-scale test is valuable for performance assessment, for re-evaluating the design basis, and for comparison to mechanical and hydraulic models of plug performance. This monitoring also helps to build confidence in the applicability of numerical modelling.

*Observe and solve practical challenges associated with Installation of Deposition Tunnel Plugs*

In the POPLU experiment plug design, construction and monitoring have provided valuable insights into repository operations. As the plug was constructed in ONKALO, there were many precautions that were taken related to repository and worker safety, such as the foreign materials review and contractor safety training. Greater detail than usual was provided in documentation, such as during public procurement for contractors and nuclear safety classifications for design documentations. Information exchange with the nuclear regulatory authorities provided valuable feedback. Practical work procedures in the underground environment will help avoid unnecessary delays in the future operations, on aspects such as availability of materials, equipment and experienced contractors. Quality assurance procedures were refined to be more efficient, reliable and transparent.

## 7.8 Conclusions

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

Demonstration of an alternative design (wedge-shaped plug) compared to the reference design (dome-shaped plug, as used in DOMPLU by SKB) has provided a greater range of experience necessary for making final decisions when preparing for repository facility operational licensing. Specifically regarding the wedge-shaped plug design, the following summaries are most relevant in future decision making and implementation of Posiva's plugging and sealing concepts:

- POPLU showed a good ternary blend low-pH concrete, coupled with a filter layer behind a wedge-shaped plug that was successfully emplaced.
- The leakage was greater than expected yet is expected to be corrected by re-grouting of the contact interface between the rock-plug.
- Modelling and monitoring techniques exist which can be utilised in other EBS components and repository operational conditions.

Based on the experiences gained in POPLU, Posiva is ready to proceed with revisions of the design basis aspects related to the plug (Posiva, 2012d) in preparation for the operational licence submission to the Finnish nuclear regulatory authority.

# 8 German Experiments on Shaft Sealing

This chapter describes the work undertaken within the German geological disposal programme that is part of the DOPAS Project and addresses the development of sealing concepts for shafts. No full-scale test as part of the German experimental work has been carried out within the DOPAS Project; the design of the shaft seal is in the conceptual design phase. The aims of the experimental work are to develop generic design concepts for shaft seals in salt and clay host rocks that comply with the requirements for a repository for HLW (Jobmann, 2013; Kudla *et al*., 2013; Herold & Müller-Hoeppe, 2013) and to carry out the necessary preparatory work in the shaft seal design project. Large-scale *in-situ* demonstration test of individual shaft sealing elements will be undertaken after the DOPAS Project.

Section 8.1 describes the design basis for shaft seals, including the safety functions assigned to shaft seals, and the existing conceptual design for a shaft seal in a salt host rock. More information on the design basis can be found in White *et al.* (2014) and more information on *in situ* tests undertaken as part of the ELSA Project are included in DOPAS (2016b). Section 8.2 describes the scope of the ELSA, LAVA, LASA and THM-Ton projects. Sections 8.3 and 8.4 summarise the main learning points associated with shaft seal construction and the main learning points from the experiments concerning material performance for the ELSA, and the LAVA, LASA and THM-Ton projects respectively. Section 8.5 summarises the achievements made in the DOPAS Project through the conduct of the German experiments on shaft sealing.

## 8.1 German Shaft Seal Design Basis

### 8.1.1 Shaft Seal Safety Functions

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 assumed for function 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, and it showed that the functional time needed can be shorter. Accordingly, the minimum functional period necessary is until the backfill in the repository drifts, access ways and emplacement fields seal the repository in response to compaction driven by host rock creep, which is achieved, depending on the boundary conditions, after some thousands up to 20,000 years.

### 8.1.2 Shaft Seal Design

The reference 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 8.1):

- The first sealing element (sealing element 1, Figure 8.1) 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 allows 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 avoid water intrusion into the repository.

- The second sealing element (sealing element 2, Figure 8.1) is made of salt concrete. Salt concrete is stable against the expected brines at that depth level and provides an alternative approach to the bentonite, thus delivering robustness to the shaft seal design.
- A third sealing element made of sorel concrete (sealing element 3, Figure 8.1) is located directly above 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 Mg-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 8.1) made of crushed salt that provides a sealing function even after the designed functional period. It is located between the two concrete sealing elements. It is expected that this salt layer would compact and reach a hydraulic conductivity that is similar to the hydraulic conductivity of the host rock (Müller-Hoeppe et al., 2012a).

This conceptual design provides a basis for the work in the ELSA, LAVA, LASA and THM-Ton projects, but does not represent the final conceptual design. The work in the projects is focused on testing and revising the conceptual design, and will feed into an update to the conceptual design after the DOPAS Project. The update to the conceptual design will take into account all of the available information (for example the results of the *in situ* compaction tests reported in DOPAS, 2016b). The relationship between the ELSA Project and LAVA, LASA and THM-Ton work is presented in Figure 8.2.

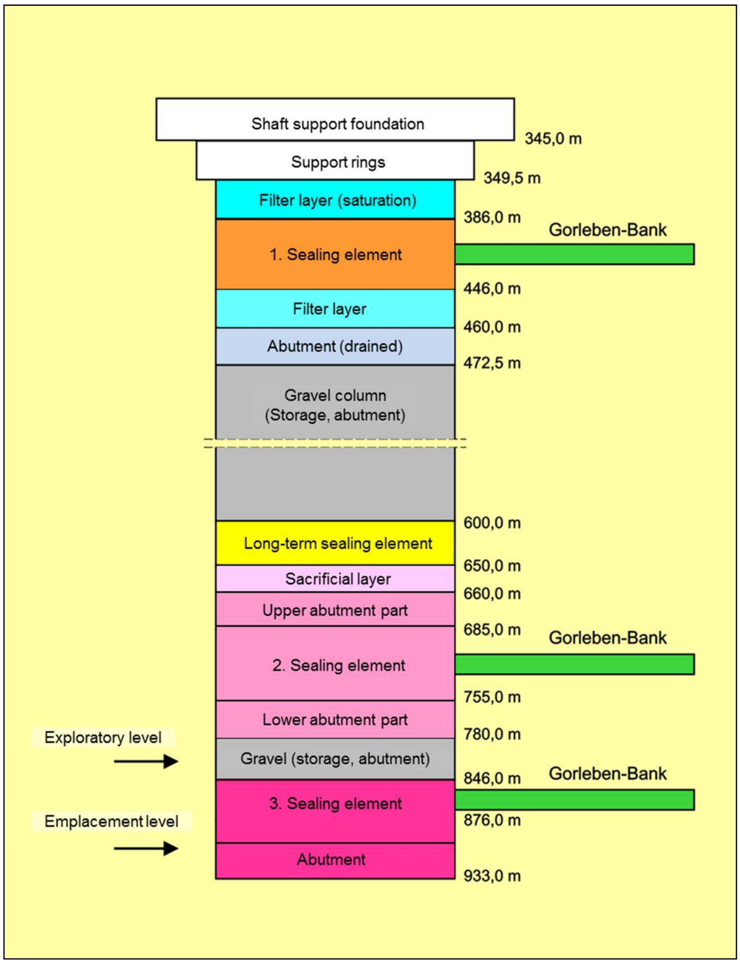



**Figure 8.1:** Schematic illustration of the German shaft seal reference conceptual design in a salt dome (Müller-Hoeppe *et al*., 2012a). The Gorleben-Bank is a folded anhydrite layer in the rock salt.

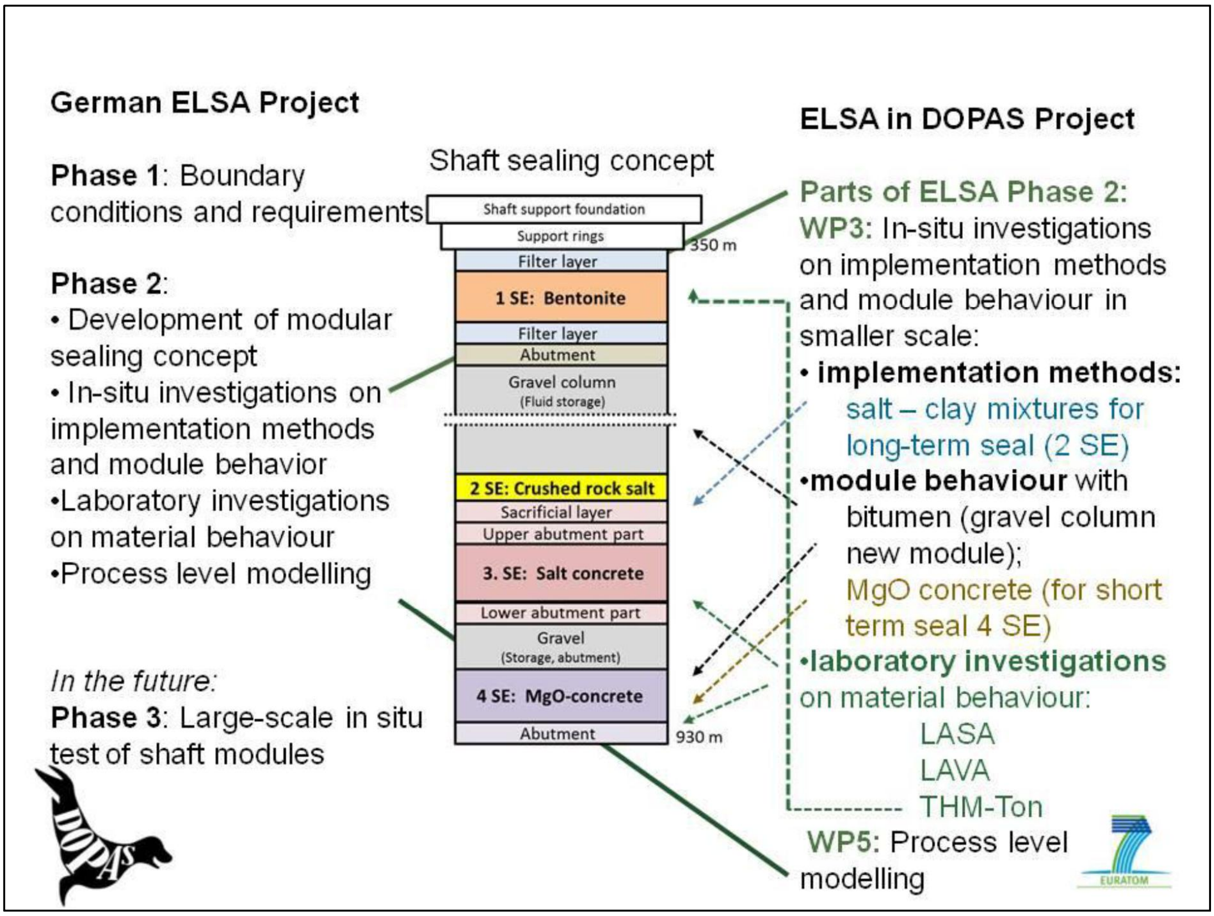



**Figure 8.2:** The relationship between the ELSA Project and the LAVA, LASA and THM-Ton projects.

## 8.2 ELSA, LAVA, LASA and THM-Ton Projects

The German work within DOPAS consists of four projects: ELSA, LASA, LAVA and THM-Ton.

### 8.2.1 ELSA Project

This project is divided into three phases[10]: Phase 1, dealing with boundary conditions and requirements for shaft seals in salt and clay host rocks ; Phase 2, focusing on development of shaft seal concepts and testing of functional elements of shaft seals in laboratory tests and in small-scale tests, including testing and calibration of mathematical models of material behaviour; and Phase 3, where a large-scale demonstration experiment of particular sealing components and adjustment of the sealing concept are planned. It has not yet been determined which components of the shaft seal will be tested within Phase 3 of the ELSA project.

The detailed objectives of ELSA are to:

- Give a summary of the state-of-the-art of long-term stable shaft sealing systems.

[10] Phase 1 was almost finished at the time of the DOPAS project start, Phase 2 of the ELSA Project has been undertaken within the DOPAS Project. Phase 3 of the ELSA Project is not part of the DOPAS Project.

- Provide documentation on how to achieve compliance of a shaft sealing system design with national and international standards and regulations (design basis analysis).
- Compile boundary conditions for shaft sealing systems in Germany.
- Define requirements for shaft sealing systems in Germany.
- Develop new and modular-based shaft sealing concepts for HLW repositories in Germany sited in both salt and clay environments.
- Perform *in situ* tests of specific functional elements (modules) of the reference shaft sealing design or alternative elements that may be incorporated in the reference design at a later date (Figure 8.1).
- Develop mathematical models to characterise the material behaviour of specific sealing elements of a reference shaft sealing design or alternative elements that may be incorporated in the reference design at a later date.

These objectives have been tackled during the Phases 1 and 2 of the ELSA project. During Phase 2 of the ELSA Project, laboratory and *in-situ* investigations on the following sealing elements were undertaken:

- Bentonite saturation (sealing element 1, Figure 8.1).
- *In-situ* investigations on MgO-concrete (sealing element 3, Figure 8.1).
- Compaction behaviour and the effects of adding clay to the crushed salt (long-term sealing element, Figure 8.1).
- Options for an additional new sealing element using Bitumen (“hard-core, soft-shell”).

Information on large-scale tests undertaken as part of the ELSA Project are included in DOPAS (2016b).

### 8.2.2 LASA Experimental Project

This project also addresses the sealing materials planned to be utilised in the shaft seals. The laboratory investigations aim at studying the thermal, hydraulic and mechanical (THM) behaviour of salt concrete (sealing element 2, Figure 8.1) and sorel concrete (sealing element 3, Figure 8.1), to provide the experimental data needed for the theoretical analysis of their long-term behaviour. The data gained is required to support demonstration of the long-term preservation of the required hydraulic conductivity of the seals.

### 8.2.3 LAVA Experimental Project

This project also addresses the sealing materials planned to be utilised in the shaft seals. The laboratory investigations of GRS aim at studying the chemical behaviour of salt concrete (sealing element 2, Figure 8.1) and sorel concrete (sealing element 3, Figure 8.1). The data gained is required to support demonstration of the long-term preservation of the required hydraulic conductivity of the seals.

### 8.2.4 THM-Ton Experimental Project

This project addresses the sealing materials planned to be utilised in drift and shaft seals in argillaceous host rocks (e.g., crushed claystone and bentonite). Therefore, selected experimental investigations relevant for the hydro-mechanical long-term material behaviour have been undertaken within the auspices of the THM-Ton Project.

## 8.3 Summary of ELSA Work on Design Basis

### 8.3.1 Boundary Conditions

To establish the geomechanical boundary conditions for design of the shaft seal, it is necessary to identify the stress-strain behaviour of the rock mass adjoining the shaft, taking into account time-dependent processes and mechanical processes related to the structure. This also has to take into account the impact of temperature and moisture as well as the expected interactions with the sealing components. Key factors are the *in situ* stress state and the convergence behaviour of the rock salt and claystone as well as the swelling pressure of the bentonite sealing elements. Of major importance is the geomechanical behaviour of the rock mass in shaft sections that intersect anhydrite-rich layers within the salt dome, e.g., the so-called "Gorleben-Bank" in the reference case Gorleben. Generally, a distinction has to be made between the initial behaviour of the intact rock mass or the initial behaviour after the profile of a drift has been reshaped and the behaviour of the rock mass after the shaft sealing elements have been installed.

Based on numerical calculations, the depth of the EDZ was estimated for Shaft Number 1 in Gorleben and for two hypothetical shafts in the two potentially suitable claystone formations identified to-date in Germany: one in northern Germany in the Lower Cretaceous formations in the Lower Saxony basin and one in southern Germany in the Opalinus Clay formation. For the shaft in Gorleben, the calculations showed two interesting aspects. As expected, the thickness of the EDZ calculated for the initial shaft sinking phase increased with increasing depth below the ground. After continuous ventilation between the two shafts had been established by means of a crosscut, this development reversed. The ventilation causes the mean temperature to drop by 20°C which leads to additional damage induced by thermal contraction, mainly in the upper part of the unlined shaft. In this area, the EDZ was calculated to extend into the rock mass for up to 7 m, whereas in the lower part the EDZ was calculated to be significantly less extensive. Although initially surprising, these results became plausible when fissures were detected in the shaft contour that extend into the rock for several metres (4-5 m). These fissures were caused by the temperature impact mentioned above. At the time, this issue was solved by heating the shaft which caused the fissures to close again. For the two sites in claystone, the expected EDZs were calculated to be between 0.3 and 1.9 m, depending on the site and depth.

Regarding the geochemical boundary conditions, data have been gathered on the phase distribution in rock salt (exemplarily for the Gorleben salt dome) and the composition of the Zechstein (Upper Permian) sequences, especially for the Leine and Staßfurt sequences. Based on the salt mineral inventories, the compositions of the equilibrium solutions were calculated. The resulting equilibrium solutions are given in Table 8.1.

**Table 8.1**: Equilibrium solutions for the salt formations of the Leine, Staßfurt sequences.

| Zechstein formation | Equilibrium solution | |
|---|---|---|
| | Phase composition of salt (%) | Ion concentration of solution (mol/kg $H_2O$) |
| Leine sequence (Na 3)<br>Bänder- u. Banksalz (z3BD/BK) | Halite – 97.1<br>Anhydrite – 0.4<br>Polyhalite – 2.0<br>Carnallite – 0.5 | $Na^+$ - 0.49<br>$Cl^-$ - 9.01<br>$K^+$ - 0.56<br>$Mg^{2+}$ - 4.13<br>$Ca^{2+}$ - 0.003<br>$SO4^{2-}$ - 0.15 |
| Leine sequence (Na 3)<br>Orangensalz (z3OS) / Liniensalz (z3LS) Basis-salz (z3BS) | Halite – 94.5<br>Anhydrite – 5.0<br>Polyhalite – 0.5<br>Carnallite – 0.0 | $Na^+$ - 4,18<br>$Cl^-$ - 6,39<br>$K^+$ - 0,92<br>$Mg^{2+}$ - 1,04<br>$Ca^{2+}$ - 0,006<br>$SO_4^{2-}$ - 0,40 |
| Staßfurt sequence (K 2)<br>Kaliflöz Staßfurt (z2SF) | Halite – 57<br>Anhydrite – 1<br>Kieserite – 16<br>Carnallite – 25 | $Na^+$ - 0,28<br>$Cl^-$ - 9,39<br>$K^+$ - 0,18<br>$Mg^{2+}$ - 4,81<br>$Ca^{2+}$ - 0,001<br>$SO_4^{2-}$ - 0,35 |

As a final result, solutions that are in equilibrium with the salt rock of the Zechstein formation are characterized by high amounts of $Na^+$, $Mg^{2+}$ und $Cl^-$, the so-called Q-, R-, IP21-Solutions (Kudla *et al*. 2013).

### 8.3.2 Requirements for Shaft Sealing Systems

The general and special requirements pertaining to the design of shaft sealing constructions, especially in salt and clay formations, are described. The requirements are derived from the legal safety requirements (BMU, 2010), the requirements resulting from existing safety assessment concepts developed in the R&D projects ISIBEL and Vorläufige Sicherheitsanalyse Gorleben (Preliminary Safety Analysis for Gorleben – VSG) for the salt option, as well as in the ANSICHT project for the clay option, from functional demonstrations, from site-specific boundary conditions, and from requirements stipulated in other specifications.

In claystone, the following requirements need to be taken into account in addition to the requirements that are also included in the design basis for the salt shaft seal: prevention of advective fluid flow from the repository or from the isolating rock mass; stable geochemical environment; adjustment to the variability in facies; material and technological requirements for the shaft liners; and use of materials with a high sorption capacity. All requirements are summarised in Table 8.2 (Kudla *et al*. 2013 and Jobmann, 2013).

**Table 8.2**: Overview of requirements for shaft seals in Germany (Jobmann, 2013 and Kudla *et al.* 2013).

| Source | Requirement | Applicable in Rock Salt? | Applicable in Claystone? |
|---|---|---|---|
| Safety requirements of BMU | Process analysis of impacts on shaft seal. | Yes | Yes |
| | If components of the shaft seal are located in the isolating rock mass, the velocities of the transport processes in the components have to be comparable with those of diffusive transport processes (sufficiently low permeability). | Yes | Yes |
| | Swelling pressures in the sealing elements are not to exceed the rock strength. | Yes | Yes |
| | If there are no technical regulations for geotechnical barriers, their construction, erection and function generally have to be verified through practical tests. (May not be necessary, if robustness can be verified by other means or if sufficient safety margins exist.) | Yes | Yes |
| | To verify the integrity of the structure, the relevant load cases and construction material properties are to be analysed. Sufficient load bearing capacity and resistance to ageing of the construction material is to be verified for the same period that the structures need to be fully functional. | Yes | Yes |
| Safety requirements of BMU | As far as necessary, immediately effective barriers have to isolate the waste for the period where barriers that are effective in the long term have not yet become completely effective. | Yes | Yes |
| | Possible requirements resulting from an analysis of release scenarios have to be identified and taken into account. | Yes | Yes |
| | If possible, redundancy and diversity are to be integrated in the shaft seal, e.g. by using several sealing elements made of different materials. | Yes | Yes |
| | The shaft seal in combination with the other barriers (e.g. drift seals) is to be assessed with regard to its importance for the safety of the repository e.g.to determine the required period of effectiveness). | Yes | Yes |

| Source | Requirement | Applicable in Rock Salt? | Applicable in Claystone? |
|---|---|---|---|
| Safety and verification concepts | Maximum period of effectiveness: 50,000 years (next glacial period).<br>Limitations regarding sealing concept (rock salt): The shaft seal has to be sufficiently tight until the hydraulic resistance of the compacting crushed salt backfill is sufficiently high. (according to current estimates, approx. 1,000 years) Consequently, the volumetric flow has to be so low that inflowing brines do not reach the crushed salt backfill in the access drifts until after 1,000 years (hydraulic requirement). | Yes | No |
| | Maximum period of effectiveness: 50,000 years (next glacial period).<br>Limitations regarding sealing concept (claystone): still pending. | No | Yes |
| | Draft design of the shaft seal (dimensioning, - properties and demonstration of general feasibility). | Yes | Yes |
| | Consequence analysis taking into account a list of features, events and processes with probable and less probable processes. Resulting requirements on functional elements are to be taken into account (if necessary, iterative optimisation). | Yes | Yes |
| | Prevention of advective fluid flow out of the repository and out of the isolating rock mass. | No | Yes |
| | Maintaining a stable geochemical environment. | No | Yes |
| Safety and verification concepts | Use of material with high sorption capacity | No | Yes |
| Technical functional verification | The design of the sealing system should be based on the technical standards and regulations DIN EN 1997-1 Eurocode 7, DIN EN 1990 Eurocode, DGGT-GDA recommendations and DAfStb guideline 2004. | Yes | Yes |
| | The individual functional elements of a shaft seal are to be designed in such a way that a functional verification pursuant to the demonstration concept can be carried out. | Yes | Yes |
| | To demonstrate sufficient hydraulic tightness, the individual elements on their own and in combination with the contact zone and the excavation damaged zone are to be considered (integral tightness). | Yes | Yes |

| Source | Requirement | Applicable in Rock Salt? | Applicable in Claystone? |
|---|---|---|---|
| | In sections where sealing elements are to be located, the excavation damaged zone is to be removed to an appropriate depth. | Yes | Yes |
| | If the sealing concept stipulates that a sealing element is to be effective immediately, the sealing element has to be either constructed of material capable of swelling or a material has to be used that - due to other properties - is in direct contact with the rock and is able to maintain this contact even under fluid pressure (e.g. bitumen or asphalt) so that the contact zone is sealed. In addition to this, the "loosened" zone that forms after the EDZ has been trimmed may have to be improved by means of technical injection measures. | Yes | Yes |
| | If non-cohesive, non-self-supporting sealing material is used, a supporting column with limited settlement capacity (settlement max. 3 % of the seal's length) is to be installed. | Yes | Yes |
| | To avoid erosion and suffusion, it is imperative to use filter layers in the sealing element. | Yes | Yes |
| | A complete and consistent data set needs to be available for all materials characterising the material's behaviour and properties. | Yes | Yes |
| Site-specific boundary conditions | If the shaft to be sealed penetrates fault zones or zones that may bear fluids, the fluid-bearing zones need to be sealed by means of sealing elements that have sufficient overlap. | Yes | Yes |
| | Depending on the pore solutions, the materials for the sealing elements are to be selected such that no significant corrosion occurs if such solutions appear. | Yes | Yes |
| | Sealing elements that are not capable of swelling are to be positioned at the lowest possible point in the shaft. | Yes | Yes |
| | The emplacement level is to be isolated from other levels (e.g. exploration level) by means of a sealing element. | Yes | Yes |
| | Where clayey and sandy facies alternate, sealing elements are to be located in the clayey facies to prevent fluid migration through the sandy facies around the barrier. | No | Yes |
| | If several aquifers are present, an interconnection is to be prevented by means of sealing. | Yes | Yes |

| Source | Requirement | Applicable in Rock Salt? | Applicable in Claystone? |
|---|---|---|---|
| | The components of the shaft seal are to be designed to withstand the maximum possible vertical fluid pressure at the site plus an additional 50 m (fixed) due to climate-induced sea-level changes. | Yes | Yes |
| Other requirements | After decommissioning, shafts are to be completely backfilled. | Yes | Yes |
| | Prior to backfilling, shaft furniture should be completely removed if this does not pose any occupational safety risk. | Yes | Yes |
| | Existing water-tight linings in areas where aquifers are present shall not be removed. | Yes | Yes |
| | Liners in horizons where seals are to be placed are removed to avoid leakages and infiltrations. | Yes | Yes |
| | In horizons where seals are to be placed, the excavation damaged zone in the shaft wall shall be removed to an appropriate depth | Yes | Yes |
| | The entrances to the drifts are secured against movement of the filling column. | Yes | Yes |
| Other requirements | Sealing elements in the shaft made of materials that are not capable of swelling (e.g. salt or sorel concrete), need to be in direct and firm contact with the rock mass. | Yes | Yes |
| | The backfill columns are installed in a dry environment. | Yes | Yes |

## 8.4 Summary of LAVA, LASA and THM-Ton Projects

The LAVA and LASA Projects aim at providing experimental data required for the theoretical analysis of the long-term behaviour of cement-based salt concrete (mass concrete with crushed salt filler, Figure 8.1, sealing element 2) and MgO concrete (Figure 8.1, sealing element 3) including the interaction with the host rock and formation water. The data gained will underpin the understanding of the long-term evolution of the hydraulic conductivity of the seals.

Samples for experimental investigations were drilled from an *in situ* seal constructed on the 945 m level of a former salt mine. At the time of sampling, the seal had been subjected to convergence of the surrounding rock salt for about ten years.

Uniaxial tests showed different deformation behaviour at increasing stress levels. Conceivable reasons for this behaviour are: (a) the cement structure of the salt concrete bears at low uniaxial stresses, and (b) at high stress, the cement structure of the salt concrete is damaged and the viscoplastic salt grit structure takes the load.

Triaxial compressions tests were used to determine the onset of dilatancy and the gas breakthrough pressure. In these experiments, failure of the specimens was determined under different radial stresses in order to better understand the complex deformation behaviour of salt concrete. In all of the tests, the gas breakthrough pressure was measured at higher deviatoric stress levels than the onset of dilatancy. The test results showed that the investigated salt concrete samples were gas-tight until the load limit was reached.

Composite samples of salt concrete cores emplaced in hollow salt cylinders were used to investigate the closing of the contact seam and the EDZ recovery under load while gas or brine was injected. Both intact and previously damaged salt concrete cores were used. While, in the dry case, gas permeability remained high, injecting salt solution led to a rapid reduction in permeability to $<10^{-20}$ $m^2$ at a confining stress of 5 MPa. With the damaged salt concrete core, permeability decrease with brine injection took much longer and reached the range of $10^{-18}$ $m^2$ in 100 days of measurement. Apparently, reconsolidation of the damaged concrete element was not achieved at a confining stress of up to 10 MPa.

Details of the experiments are described in the LASA final technical report on ELSA-related testing on mechanical-hydraulic behaviour (Czaikowski *et al*. 2016).

Additionally, the chemical stability of cement-based sealing materials is of vital importance for the longevity of the sealing elements. In case of an enduring contact between aqueous solution and the sealing element, dissolution and precipitation processes can occur which eventually might result in changes of porosity and, subsequently, mechanical stability. Laboratory tests carried out by GRS aim to investigate the reaction path and the diffusive and advective transport mechanisms in salt and sorel concrete in contact with Mg-rich and NaCl solutions.

The total chemical reaction path of solution penetrating a geotechnical barrier can be reproduced by conducting cascade experiments until the thermodynamic equilibrium between the original solution and the solid material is attained. In this way, chemical reactions which may occur following intrusion of brine into a sealing element can be simulated in a practical experimental time. The equilibration time in system sorel concrete / NaCl-solution was determined in pre-experiments. As a result, each cascade in the cascade experiment in sorel concrete / NaCl-solution system needs a minimum of 11 days. Equilibration time between concrete and NaCl solution is only valid for a system with powdered concrete; for solid samples a longer equilibration time is expected because of the smaller specific surface area contacted by the solution. The experiment regarding the development of solution composition in batch experiment with salt concrete / Mg-rich-solution is still in progress because the equilibrium has not yet been reached at the time of writing.

An advection experiment with a combined sample of salt concrete / rock salt is in progress. The contact zone has closed using a radial pressure up to 10 MPa and a flow with NaCl-solution until a permeability of $10^{-18}$ $m^2$ was reached. Afterwards radial pressure was minimized to 2 MPa for relaxing sample. In a subsequent step, the NaCl-solution was changed to a Mg-rich-solution. Permeability decreased in the beginning and after two months of contact with the Mg-rich-solution, permeability started to increase again. This phenomenon results from chemical processes in the salt concrete as former investigations at GRS have shown. If the Mg-rich-solution is brought in contact with salt concrete, free hydroxide ($OH^-$) is fixed by magnesium and brucite ($Mg(OH)_2$) is precipitated. As a result, pores are clogged by brucite and pH decreases to 8-9 (phase 1). As a result of the pH decrease, Portlandite ($Ca(OH)_2$) becomes unstable and decomposes to Ca- and hydroxide ions. After consumption of all Portlandite, the pH decreases further and stabilizing CSH-phases are dissolved. Now concrete loses its stability and permeability starts to increase (phase 2).

These experiments are on-going as dissolution needs more time compared to the batch- and cascade-experiments with powdered concrete. Details of the experiments - available so far - are described in the LAVA final technical report on ELSA-related testing on chemical-hydraulic behaviour (Jantschik *et al.* 2016). Recently, extensive calculations have been undertaken to enable interpretation and further prognosis of the experimental data. This work is still underway at the time of writing of this report.

Within the THM-Ton programme, crushed claystone and MX80 bentonite was used in the experiments. It is convenient to use the excavated material immediately for backfilling the repository openings without further treatment. Therefore, raw crushed claystone with grain sizes up to a diameter of 10, 20 and 32 mm was tested. In addition, fine-grained claystone powder with grain sizes of d <0.5 mm was mixed with the MX80 bentonite of d <0.5 mm in different ratios. Large-scale samples of 280 mm diameter and 640-680 mm lengths were prepared with the coarse crushed claystone of grain sizes of d <32 mm and d <20 mm. The initial dry densities reached by hand stamp, vibration and slight compression vary in a range of 1,450-1,820 kg/m³. The samples were compacted in the GRS big triaxial apparatus with measurement of permeability.

The water permeability of the compacted claystone-bentonite mixtures was determined by flowing synthetic clay water through the samples in Oedometer cells. All of the compacted mixtures exhibited very low water permeabilities: $K_w = 2\times10^{-19}$ m$^2$ at 80COX+20MX80, $K_w = 3\times10^{-20}$ m$^2$ at 60COX+40MX80, and $K_w = 2\times10^{-20}$ m$^2$ at 40COX+60MX80. In case of the crushed claystone with grains of d <10 mm, the water permeability becomes very low, too, $K_w < 1\times10^{-19}$ m$^2$, as the porosity is below 30%. The very low water permeabilities of the compacted mixtures are close to that of intact rock ($K_w < 10^{-20}$ m$^2$).

It can be stated that all the mixtures investigated exhibit favourable geotechnical properties with respect to their barrier functions allowing them to be used as sealing material. Details of the THM-Ton experiments are described in the final report on the sealing behaviour of fractured claystone and seal materials (Zhang, C.-L. 2016).

## 8.5 Achievements of German Experiments on Shaft Sealing

The *in-situ* work documented in Section 8.5, has used the outputs from the laboratory work (LAVA, LASA and THM-Ton Projects), discussed in Section 8.4, as the basis for the experimental work (ELSA Project).

### 8.5.1 Sealing Material Improvements

During the experimental work, improvements to specific sealing elements in the current reference concept have been developed. Evidence has been provided that the long-term sealing element (Figure 8.1) 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 the installation. Compaction of the material can be improved and a lower initial porosity be achieved when a mixture of crushed salt and clay is used instead. Laboratory and *in situ* experiments suggest that a sufficient initial *in situ* compaction of the mixture (porosity of about 10%) is possible which ensures a sufficient low permeability. In case of fluid movement into the sealing element, the clay admixture starts to swell. Due to this swelling, the fine pores in the crushed salt 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 (Figure 8.1) 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, in addition to the gravel, a small part of the gravel column can act as a sealing element as well. In contrast to the bentonite sealing element (sealing element 1, Figure 8.1), 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).

### 8.5.2 Compliance Evaluation of the Salt Concrete Sealing Element as an Example

The German strategy for demonstrating compliance of the seal designs with the design basis has recently been developed during the Review and Evaluation of the Instruments for Assessing Safety of Higher-Activity Waste (HAW) Repositories (ISIBEL) project (Weber *et al*., 2011) and the VSG R&D project. It is a semi-probabilistic, reliability-oriented concept using partial factors (referred to as safety coefficients in Figure 8.3) and is based on the internationally recognized Eurocodes. The Eurocodes are a series of ten European standards, with each of these codes consisting of several parts (EC-JRC, 2008). In engineering, it can thus be considered as state-of-the-art for demonstrating the load-bearing capacity of a structure, i.e., the ability of a structure to perform to the required standards under induced loads.

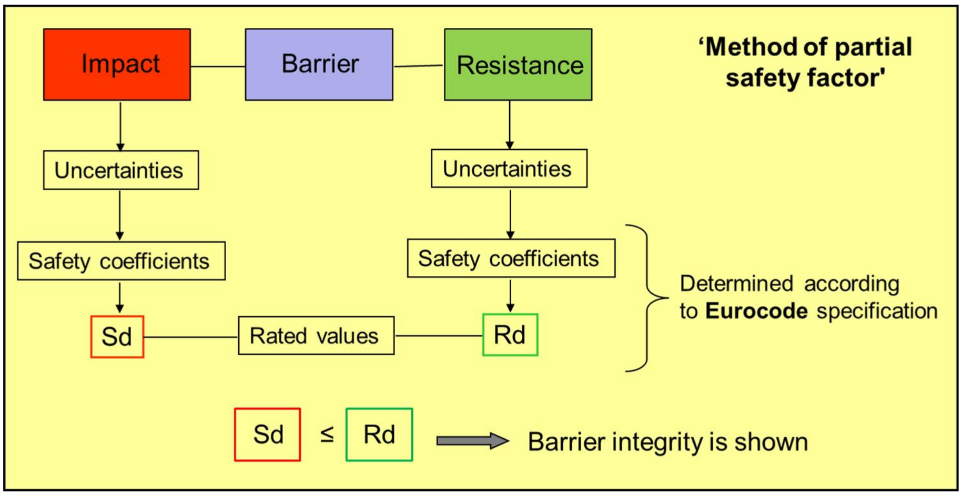



**Figure 8.3**: General principle of the partial safety factor method.

In this approach, specific requirements are judged to have been met if the designs meet criteria (limiting values) evaluated by means of “assessment cases” (or load cases). The term “assessment cases” was chosen to be analogous to the term used in long-term safety assessments as, in addition to the load, other parameters need to be taken into account as well. The assessment cases are derived from the combinations of loads on a structure and from the specific system characteristics.

The demonstration of compliance is carried out by conducting a limiting value evaluation of the loads on a structure and the resistance of the structure to those actions, e.g., the (existing) stresses are compared with the nominal design stresses which can be calculated from the material strength. Both loads and resistances are determined from distribution functions. The limit state describes the state of the structure where it just barely meets the requirements. If this state is exceeded, then the structure no longer complies with the design requirements. Accordingly, in order to meet the design requirements, the resistances need to be sufficient to withstand the loads (actions) on the structure.

To account for uncertainties in the representative values of the loads (actions) and in the properties of the structure, partial factors are allocated to the values in question. These are coefficients that are applied to both the loads acting on the structure and the resistances of the structure. Loads are multiplied by partial safety factors and, thus, increased, whereas resistances are divided by partial factors and, thus, decreased. The design values or so-called “rated values” for the individual assessments are derived from the characteristic values of the loads on, and the properties of, the structure, combined with the related partial factors. This approach is illustrated in Figure 8.3. More details and an application example can be found in Herold & Müller-Hoeppe (2013).

One of the sealing elements used in the reference concept for the Gorleben shaft sealing is to be constructed of salt concrete (sealing element 2, Figure 8.1). At the location of the seal, the contour is trimmed off for 0.6 m so that the final diameter at the location is 8.83 m. The total length of the sealing element is 60 m, however, as this location includes the Gorlebenbank, the effective length of the sealing element is assumed to be only 50 m (Müller-Hoeppe *et al.*, 2012a).

***Permeability Estimates***

Tightness needs to be demonstrated for the integral permeability at the seal's location. This assessment has to include the three sub-systems sealing element (SE), contact zone (CZ), and EDZ, which act parallel to each other. At the location of the seal, a maximum mean integral permeability of $k_{req} = 7\times10^{-19}$ m$^2$ is required, which was defined as the highest value measured *in situ* to date (Müller-Hoeppe *et al.*, 2012a; Engelhardt *et al.*, 2011). This means that under the existing conditions, the sealing element has to have at least this mean permeability in order to be able to delay brine intrusion into the repository for a sufficiently long period. This permeability is the integral permeability of the construction, calculated as a mean over the cross-section including the CZ and EDZ. During construction, this has to be demonstrated by structural analysis verifications. Within the scope of the safety case, possible limit states and failure cases are investigated by means of a long-term safety analysis. This analysis takes into account the spatial variability of the permeability in the sealing element. The integral permeability that has to be demonstrated on the resistance side consists of the individual permeabilities of the components, related to the surface as follows:

$$k_{int} = \frac{k_{SE} \cdot A_{SE} + k_{CZ} \cdot A_{CZ} + k_{EDZ} \cdot A_{EDZ}}{A_{SE}} \qquad \text{Equation 1}$$

The mean permeability ($k_{int}$) is compared with the required limit value ($k_{req} = 7\cdot$x $10^{-19}$ m$^2$). At this point, we refrain from equipping the individual components of the design value of the resistance with partial factors. The salt concrete sealing element is part of the overall shaft seal, which is to delay potential brine intrusions. The assessment of the hydraulic system as a whole is carried out in a final probabilistic long-term safety analysis which takes into account the distribution functions. This covers model uncertainties and failure cases. Partial factors for individual representative characteristic values are not taken into account. The representative characteristic values, especially of the permeability, were used as design values. For the permeability, the values used are the means of the existing distribution.

In accordance with Eurocode specifications (DIN EN 1990), design values can be determined by empirical/deterministic methods as well as by statistical methods. The 95% confidence interval for the mean value is considered to be a conservative estimate of the mean. Depending on the individual case, the characteristic value can also be calculated as 5% fractile. Both are possibilities to determine the design value of the resistance using the characteristic value. In addition to this, a direct determination of the design value for ultimate limit state verifications is possible.

In the following, results obtained from the three methods are given. As an example, the mean permeabilities for the sealing element, the CZ, and the EDZ are determined using selected test series.

*Properties of the sealing element*

The initial diameter in the unlined part of the shaft is 7.63 m. At the location of the seal, the EDZ of the contour is trimmed off for 0.6 m. Thus, the diameter of the salt concrete sealing element is 8.83 m, which corresponds to a cross-section area of the sealing element of $A_{SE}$ = 61.24 m². An additional deviation needs not be taken into account.

Salt concrete was used in the Project "Asse-Vordamm" (Müller-Hoeppe and Eberth, 2009). Based on experience from *in-situ* tests, the production of a vertical sealing element made of salt concrete can be demonstrated. As a result of tests on the structure, characteristic values concerning the fluid and gas permeability of the salt concrete as well as characteristic values of the contact joint and the surrounding EDZ are known. According to Müller-Hoeppe *et al.* (2012b), only three characteristic values were determined *in situ* for the seal's permeability to fluid. It is between $4\times10^{-20}$ and $9\times10^{-21}$ m². But there is a large database for the gas permeability of the material. As explained above, by means of statistical methods, these measuring data can be used to determine characteristic values of the permeability (Table 8.3).

**Table 8.3**: Summary of the design data of the mean integral permeability.

| Element | Surface area $A_i$[m²] | $X_k$ as 5% fractile [m²] | $X_k$ as 95% confidence interval [m²] | $X_d$ as directly determined design value [m²] |
|---|---|---|---|---|
| Structure | 61.24 | $3\times10^{-22}$ | $5\times10^{-23}$ | $3\times10^{-21}$ |
| Contact zone | 0.84 | $4\times10^{-22}$ | $7\times10^{-23}$ | $1\times10^{-20}$ |
| EDZ | 0.84 | $2\times10^{-21}$ | $1\times10^{-22}$ | $8\times10^{-20}$ |

*Properties of the contact zone*

The contact zone between a sealing element and surrounding rock mass is characterized by the material properties, the installation conditions, and the grain size distribution in the rock mass. The wet salt concrete is compacted during installation. It spreads evenly within the space designated for the seal and adheres to the rock mass after settling. Based on (DAfStb, 2004), the expansion of the contact zone is assumed to be two-times the maximum opening diameter. As the exact properties of the rock mass at the location of the seal are not sufficiently known, the contact joint is assumed to have a thickness of 30 mm as specified in (DAfStb, 2004). Due to its small extent compared with the system as a whole, it is not necessary to additionally take into account a geometric deviation. The annular contact joint has a surface area of $A_{CZ}$ = 0.84 m².

Exemplary permeability properties of the contact joint are derived from the project "Asse Vordamm". Measurements in the contact zone between salt concrete and rock salt taken at the walls and the floor yielded permeabilities between K = $1\times10^{-23}$ and $7\times10^{-23}$ m² (Müller-Hoeppe and Eberth, 2009 and Müller-Hoeppe, 2010). Using a similar method as the one used to determine the design value of the permeability of the salt concrete structure, the mean permeability of the contact joint can be determined.

It can be stated that permeability in the range of the required mean value is feasible. This is indicated by the individual value $6.5\times10^{-19}$ m². Based on the three statistical methods mentioned above, the characteristic or design values are derived from the data measured in the floor and wall drillings (Table 8.3).

*Properties of the excavation damaged zone*

According to calculations, the plastic zone of the EDZ caused by excavation at the location of the 2nd sealing element expands for 0.66 m from the shaft contour into the rock. Variations due to seasonal or thermal aspects are not taken into account at this point as they can be controlled by technical measures. After the EDZ has been trimmed off for 0.6 m (Müller-Hoeppe *et al.*, 2012a), an EDZ of 0.06 m remains. This is based on the additional assumptions that trimming off is carried out with as little damage to the rock as possible and that the sealing element is installed as soon as possible so that re-damage of the rock mass close to the contour is kept to a minimum. The newly developed damage should be estimated prior to installation and should be taken into account in the permeability calculations. In this case, we refrain from doing so.

From this new contour ($r_N$ = 4.415 m), the remaining EDZ, which is assumed to be perfectly circular, extends 0.06 m into the rock. Taking into account the contact zone, an EDZ area of $A_{EDZ}$ = 0.84 m² remains.

In addition to the actual depth of the EDZ, the permeability of the damaged zone needs to be determined. As both depend on a number of different and site-specific factors, it is essential that they are determined by means of *in-situ* measurements. Due to inhomogeneities in the rock mass, for example, the EDZ may not expand in a perfect annulus around the contour. Characteristically, the region close to the contour has the highest permeability. The greater the distance to the contour, the more the permeability approaches the initial permeability of the rock mass (Hunsche *et al.*, 2003).

According to (Wagner, 2005), this is the reason why it is reasonable to identify a limit permeability to be able to differentiate between permeable and technically impermeable regions and to determine the exact characteristics of the EDZ. In (Wagner, 2005), a limit permeability is identified for the rock salt in question and is set to $k_{limit} = 10^{-19}$ m².

However, this value cannot necessarily be considered as universally valid. In fact, it is recommended to define a limit value that takes into account the site-specific parameters that influence the permeability. The effective or integral permeability of the EDZ can be determined by means of extrapolation using existing series of measurements. The measurement series used as an example for the permeability can also be used to derive estimated mean values for the EDZ.

Based on the three statistical methods mentioned above, the characteristic or design values are derived from the data measured in the floor and wall drillings (Table 8.3).

Over time, the creep behaviour of the surrounding rock salt mass leads to a healing of the remaining EDZ. The permeability of the EDZ changes and, in the long term, reaches the level of the intact rock mass. This effect, which has a positive influence on the sealing properties of the salt concrete element, will not be taken into account in this simplified safety analysis. As a conservative assumption, only the increased permeability at the beginning of the lifetime of the sealing element will be considered.

*Determining the integral permeability*

The characteristic values derived in the previous section will be used in Equation 1 to determine the integral permeability. Table 8.3 summarises all relevant data.

For the three calculation methods used, this leads to an integral permeability $k_{int}$ calculated as mean over the cross-section:

| | |
|---|---|
| 5% fractile | $3.3\times10^{-22}$ m² |
| 95% confidence interval | $5.2\times10^{-23}$ m² |
| Directly determined design value | $4.2\times10^{-21}$ m² |

A comparison with the limit criterion selected for the permeability of $k_{req} \leq 7\times10^{-19}$ m² shows that, based on the assumption made in this context, the integral permeability to be expected at the location of the seal is sufficiently lower than the targeted limit criterion. This demonstrates that, based on the assumptions made and provided they are implemented correspondingly, a sufficiently low integral permeability can be achieved for the salt concrete sealing element 2.

However, the integral permeability alone is not sufficient to demonstrate tightness but rather the resistance of the sealing element as it opposes any actions or its delay effect which both result from the integral permeability and other properties of the sealing element.

### *Flow time*

In the previous section it is shown that the sealing element and, thus, the shaft seal as a whole is not completely tight. Complete tightness is practically not feasible. Instead, the aim is to achieve a state where the sealing element and, thus, the shaft seal as a whole can be considered to be technically tight. This means that during the lifetime of the shaft seal, there is no complete flow through the structure.

The long-term safe containment of the radioactive waste is to be affected by the rock mass of the salt diapir that surrounds the repository. Based on these requirements, the lifetime or functional life of a shaft seal in a salt formation depends on the compaction properties of the backfill material in the repository. Only after the crushed salt in the drift has compacted in such a way that its permeability is lower than that of the drift seals and approximates that of the surrounding intact rock, the barrier function of the shaft seal is no longer absolutely necessary. According to current calculations, this process takes approximately 1,000 years (Müller-Hoeppe *et al.*, 2013b). This is, thus, the minimum period for which the shaft seal has to delay brine intrusion. A premature brine flow into the backfill material would influence the further compaction and thus, the evolving pore pressures and may even stop the latter process. In this case, formation of migration paths could not be excluded.

The salt concrete sealing element 2 considered here, is located in the middle of the shaft seal. Brine at the top of the sealing element would mean that there is brine flow through the upstream sealing and buffer elements of the shaft seal or that their retention capacity has been exhausted. These brines are assumed to have a density of $\rho$ = 1,200 kg/m³. Based on these assumptions, it is further assumed that the load on the salt concrete sealing element is the result of a hydrostatic pressure caused by a brine column that extends to the ground level.

The flow time through the sealing element is calculated to be $t$ = 485 years. When the sealing element is completely saturated, the flow through it is stationary. The resulting volumetric flow $\dot{V}$ is calculated to be $\dot{V}$ = 0.05 m³/a. Beneath the salt concrete sealing element and the following salt concrete abutment, a further section of the shaft column is backfilled with hard rock gravel. This section is 66 m long and upon installation and has a porosity of 38% and a pore volume of about 1,150 m³. It is calculated that the volumetric flow determined above would take approximately 23,000 years to fill this reservoir below the 2$^{nd}$ sealing element. The resistance of the sealing element is sufficient to prevent premature flow of brine to the downstream barriers and repository areas.

### *Results and Assessment*

The calculations above show that the delay effect of the second sealing element of salt concrete can be considered to be sufficient, a result which is relevant to the work of both DBE TEC and GRS. The delay of brine intrusion by this component of the shaft seal is sufficiently long. Thus, the sealing element is considered to be technically tight. In addition to hydraulic tightness, it is demonstrated that the functional life is sufficiently long. This simplified safety assessment does not take into account the sealing and buffer effects of the upstream and downstream elements. The combination of subsystems is part of the long-term safety analysis. The lifetime or functional life of the shaft seal as a whole can, thus, be estimated to be significantly longer.

In the previous sections, the integral permeability of the sealing element as characteristic value of the resistance was determined as an example in a simplified way. To simplify the presentation, the various characteristic permeability values were taken from literature. A real safety analysis would require a reliable database which allows statistically verified statements about characteristic values, e.g., of the permeability of the EDZ, and the application of suitable variability factors. As the integral permeability would be part of a subsequent probabilistic long-term safety analysis, we refrained from using partial factors. However, when directly determining design values according to the standard “partial factors”, the latter are included.

For the sealing element as well as for the abutment, only individual assessments of the complete analysis shown in Figure 8.1 were carried out. The aim was to illustrate the general methodology using individual assessments as examples. The assessment of the settlement stability of the gravel column was carried out using corresponding partial factors. When assessing the tightness, we refrained from using partial factors. Tightness and functionality were verified by means of calculations. A final probabilistic analysis of the long-term safety of the shaft seal as a whole investigates the system’s behaviour at various limit states and is, thus, conservative. The application of additional partial factors to determine tightness and functionality is thus not necessary at this point.

## 8.6 Key Conclusions

From the *in-situ* and laboratory investigations performed so far, it can be stated that the sealing abilities and the permeabilities of the individual sealing elements will in principle be good enough for an application in a shaft sealing system. This has been underpinned by applying the safety assessment method illustrated above for a salt concrete sealing element. 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.

# 9 Progress on the Technical Feasibility of Repository Plugs and Seals in WP2, WP3 and WP4 of the DOPAS Project

This chapter discusses the progress that has been made on the technical feasibility of repository plugs and seals during WP2, WP3 and WP4 of the DOPAS Project. This covers the work on the design basis, design, siting, construction and performance in the experimental activities carried out within the framework of the DOPAS Project. The discussion is structured as follows:

- In Section 9.1, the application of systems engineering approaches during the DOPAS Project is discussed, and the benefits this has delivered to the design process, in particular the evaluation of designs against the design basis, are discussed.
- In Section 9.2, the progress that has been made in demonstrating that the reference (and alternative) plug and seal designs tested in the DOPAS Project meet safety functions specified in disposal concepts is discussed.
- Section 9.3 discusses technical issues resolved during the DOPAS Project, focusing on the technical solutions for each of the components contained in plug and seal designs, the technical solutions related to siting and construction, and technical solutions to monitoring the performance of plugs and seals.
- Section 9.4 discusses the operational issues resolved during the DOPAS Project.

## 9.1 Application of Systems Engineering Approaches to Repository Design

The DOPAS Project has used a systematic requirements-based approach to defining the design basis for the plug and seal designs, and for evaluating the performance of the plugs and seals with respect to the design basis. The approach adopted is consistent with approaches adopted in other industries (e.g. NASA, 1995) but includes specific modifications suitable for application to the design of repository systems.

The development of parallel reference and experimental designs, as undertaken in the DOPAS Project is consistent with the practice of concurrent engineering (Carter and Baker, 1992).

The work in the DOPAS Project has demonstrated how a structured hierarchy of requirements can be a good basis for identifying and evaluating requirements at different levels of detail (see Chapter 3 and DOPAS, 2016a, for further details on the hierarchy). In particular, the evaluation of the performance of the DOPAS experiments has focused on the evaluation of requirements expressed as both safety functions (which are also referred to as system requirements in the terminology adopted within the DOPAS Project, see Section 3) and design specifications.

In the evaluation work presented in this report, intermediate requirements are addressed by developing requirements at a lower (i.e. more detailed) level in the hierarchy. For example, in several of the tables presented in this report, the design specification related to bentonite hydraulic conductivity is expressed in terms of density (and, in some cases initial water saturation). Examples include FSSDS07 in Table 4.1, EPSPDS05 in Table 5.1 and DOMDS06 in Table 6.1. Design specifications should be expressed in a way that facilitates compliance demonstration, for example using quality control procedures during repository operation; testing of the bentonite density would be possible during repository operation but regular testing of hydraulic conductivity would be more challenging and would impact more significantly on repository operations.

The outcomes of the work on the application of systems engineering approaches to repository design is summarised in Section 3, and DOPAS (2016a) present the definitions of the requirement hierarchy applied in the DOPAS Project in more detail. This work has demonstrated how a structured approach to requirements management can be applied in repository design. The structured approach has been captured in the DOPAS Design Basis Workflow (Figure 3.1). Many programmes have been adopting requirements-based design approaches, but there has been little work published on the application of systems engineering through the iterative development of designs. In particular, the manner in which systems engineering approaches and structured hierarchies of requirements can be used to demonstrate compliance of repository designs with requirements and feedback into modified designs has not been illustrated with respect to repository systems previously. The work in the DOPAS Project, if adopted more widely by waste management organisations, provides an approach to using systems engineering in a more structured fashion in repository projects.

In addition to the use of systems engineering approaches, the design of the DOPAS experiments has made significant use of Eurocode standards. Structural Eurocodes are a set of harmonized European standards for the design of buildings and civil engineering structures. There are 10 Eurocodes made up of 58 parts that will be adopted in all EU Member states (for example, full implementation of the Eurocodes in the UK took place on 31 March 2010 when the existing British Standards were withdrawn). The application of the Eurocodes provides a platform for structural designs adopted in one programme to be more readily transferred for application in another programme.

## 9.2 Demonstration that Designs Meet Safety Functions

Evaluation of the compliance of reference designs of plugs and seals with the design basis has been addressed in the DOPAS Project at two levels:

- Validation of performance against safety functions (system requirements), using a mixture of quantitative evidence and qualitative arguments (Section 9.2.1).
- Verification of the performance of the experiments against design specifications using measurements and monitoring at a range of scales, including laboratory tests and full-scale experiments (Section 9.2.2).

### 9.2.1 Validation of Safety Functions

Work in WP2, WP3 and WP4 of the DOPAS Project has allowed the compliance of plug and seal designs with safety functions to be evaluated. The conclusions for FSS, DOMPLU and POPLU are presented in Sections 4.7.1, 6.7.1 and 7.7.1 respectively. The safety function compliance evaluation conducted for each experiment reflects the current observations. Additional analysis of the compliance is still ongoing and experiment dismantling and long-term assessment calculations will also be used to assess the compliance of the designs to the safety functions.

At the present stage, all of the experiments have helped to build confidence that the safety functions can be met by the designs tested in the DOPAS Project:

- For the Andra reference drift and ILW vault seal, the bentonite seal and concrete containment walls have been emplaced in the FSS experiment, showing that the design is technically feasible at full scale.
- For SKB's reference deposition tunnel plug, the performance of the DOMPLU experiment up to 30 September 2014, has contributed to demonstrating compliance with the three safety functions identified for the plug (confinement of backfill, support for backfill saturation and provision of a water flow barrier). Evaluation of gas

tightness of the plug has not yet been possible, as this requires saturation of the bentonite seal.

- For Posiva's alternative wedge-shaped deposition tunnel plug, the materials testing and development programme has contributed to demonstration that the plug system provides favourable and predictable mechanical, geochemical and hydrogeological conditions. The concrete structure itself confines the backfill, yet the leakage due to the tunnel interface grouting needs to be enhanced to further confirm backfill confinement. Experience from early pressurisation has built confidence that the POPLU plug will contribute to mechanical stability of the rock based on rock displacement monitoring. Further monitoring during the build-up of pressure on the plug will address these safety functions.

With respect to EPSP, the Czech programme is in its initial stages and specific safety functions have not yet been finalised. It would be premature therefore to evaluate the performance of the EPSP experiment with respect to the safety functions to be assigned to a reference design. Nonetheless, as discussed in Section 9.2.2, the performance of the experiment with respect to experiment-specific design specifications provides confidence that plugs based on the components used in EPSP could provide safety functions consistent with those likely to be required in a repository.

Similarly, the experiments conducted in the German work as part of the ELSA, LAVA, LASA and THM-Ton projects are focused on materials development and small-scale testing rather than a full-scale test of (aspects of) a reference or alternative plug and seal design. Nonetheless, the results of these experiments also give confidence that shaft seal designs can be developed that will be expected to meet the safety functions of shaft seals in a German repository.

### 9.2.2 Verification of Design Specifications

The compliance of the experiments with the safety functions is also met by linking the safety functions to more detailed requirements (design specifications). In the evaluation of the DOPAS experiments undertaken within the scope of the DOPAS Project, there has been a focus on key design specifications, which 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 discussed in this report. On-going evaluation of the experiments undertaken within the DOPAS Project will be carried out by WMOs following the completion of the DOPAS Project, and will consider the full range of issues collated in the design basis.

However, the evaluation of the key design specifications undertaken as part of the DOPAS Project has demonstrated that the designs of plugs and seals implemented in the Project are consistent with requirements. Common key design specifications that are addressed in most of the design bases include:

- Compressive strength of concrete: The compressive strength of the concrete is a design specification recognised in the list of key design specifications for all experiments. This is because a key function of the plugs and seals is to resist the pressures exerted on them. All experiments met this design specification. This is because, in part, the compressive strength required was the strength assumed in design calculations. In some cases, mechanical properties like strength were known from the results of pre-existing testing and, in other cases, had to be verified during material development. However, it was also necessary to test the materials at full-scale to demonstrate that laboratory conditions could be replicated at full-scale and in underground conditions.

- Tensile strength of concrete: The stresses on plugs and seals are reoriented as the forces are transmitted through the concrete bodies. This results in the front part of concrete domes being in tension, and, therefore, for these structures it is also important to consider the tensile strength of the structures.

- pH of concrete leachate: For composite plugs and seals incorporating both concrete and bentonite components, and repositories in which leachate from the concrete can migrate and interact with other elements of the EBS (e.g. backfill and buffer), it is important that the concrete leachate does not affect the long-term performance of the bentonite. This can be achieved by developing a concrete with a leachate pH in relevant groundwaters of ≤11. This has been achieved by all concrete mixes developed in the DOPAS Project with the exception of the EPSP shotcrete mix where a pH of 11.7 was specified.

- Curing temperature of concrete: For the hydraulic performance of the concrete in plugs and seals, it is important that cracking of the concrete during curing is minimised. Absence of cracking owing to thermal stress is ensured by specifying a maximum curing temperature, the value of which is dependent on the design of the concrete in the plug or seal. In addition, cracking of concrete can result from external stresses, and crack formation can be monitored using strain gauges and/or through visual inspection of exposed surfaces of the concrete. In the DOPAS experiments, maximum curing temperatures in the range 50°C to 60°C were specified in FSS, EPSP and POPLU. 60°C is generally regarded as an appropriate maximum temperature to avoid the formation of thermally-induced cracks and to prevent the transformation of the cement hydration products that may induce secondary ettringite formation. The maximum temperature for FSS was 50°C, as this was regarded to be appropriate for the concrete in a test box at a surface facility. The thermal conductivity of the argillite host rock in Cigéo is significantly lower than that of the test box concrete, and a higher temperature limit of 60°C is expected to be specified for SCC application in the repository. For the DOMPLU experiment, a much lower temperature of 20°C was specified which is consistent with the relatively small thickness of the non-reinforced concrete dome and the unique application of a cooling system within the design. The cooling system was introduced to reduce the impact of hydration heat on the concrete temperature, to facilitate release of the concrete dome from the host rock in order to allow a wider space for contact grouting, and to pre-stress the concrete dome prior to contact grouting. Even though non-reinforced concrete was also used in FSS, a cooling system was not implemented as there was no requirement to ensure watertightness of the concrete contact zone (after contact grouting) in FSS, and, therefore, there was no need to ensure full release of the concrete walls from the test box lining. The functions of the concrete walls in FSS is to act as mechanical support to the bentonite clay core.

- Density/swelling pressure of bentonite: The hydraulic performance of bentonite sealing sections within the DOPAS experiments is defined by key design specifications related to bentonite density (no bentonite density is specified for the POPLU experiment because no bentonite sealing section behind the concrete wedge was included). Compliance with bentonite density requirements in the DOPAS experiments (FSS, EPSP and DOMPLU) has been demonstrated using mass balance and quality control approaches.

In addition to these common key design specifications, other design specifications have been highlighted in this report. Low leakages are targeted for the DOMPLU and POPLU experiments, whereas an exact hydraulic conductivity value has been specified for the EPSP experiment. EPSP has defined a hydraulic conductivity value because the experiment is focused on development of experience and expertise rather than testing of a reference concept, so specifying a leakage rate was not appropriate.

The DOMPLU experiment and the SKB deposition tunnel plug reference design contains design specifications on more components than the other experiments. This reflects the greater number of components in DOMPLU compared to FSS and POPLU, and the status of SKB's programme compared to the Czech programme; the SKB programme is closer to licensing than the Czech programme, and, therefore, the design basis for the deposition tunnel plug is developed to a greater degree. Design specifications placed on the DOMPLU experiment include those related to release of the concrete dome from the host rock, the pressure on the concrete, displacement and nature of groundwater flow for the delimiters, and the overall gas permeability of the plug.

## 9.3 Technical Issues Resolved in the DOPAS Project

The DOPAS Project has addressed a large number of technical issues associated with the design and emplacement of materials and monitoring systems for plugs and seals, and also the siting and construction of plug and seal locations. The achievements in the DOPAS Project with respect to these issues are discussed below.

### 9.3.1 Siting of Plug/Seal Locations

Siting of the plug and seal locations for the DOPAS experiments has been based on a variety of approaches. The FSS experiment was sited in a surface facility owing to cost, logistics and monitoring considerations. The EPSP experiment was located in a near-surface former mineral exploration facility, and, therefore, had to include rock grouting and other works to improve the ground conditions. The DOMPLU experiment was located in the Äspö HRL, and a site in the deepest part of the facility was chosen to best replicate the pressure conditions expected at the disposal horizon in the Forsmark repository. The POPLU experiment was located in the experimental area of the ONKALO facility which is part of the future operational repository and thus had more stringent requirements for site preservation.

There were, therefore, significant constraints on the siting of the full-scale experiments undertaken within the DOPAS Project. Nonetheless, the specific locations selected for the DOMPLU and POPLU experiments were identified through testing of specific methodologies by SKB and Posiva. This included the first successful application of Posiva's RSC methodology to the siting of deposition tunnel plugs.

### 9.3.2 Excavation of Plug/Seal Locations

The DOPAS Project has allowed evaluation of a range of techniques for excavation of plug and seal locations, in particular, techniques for the excavation of slots into which concrete structures can be cast. 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).

The experience of application of the hydraulic wedge splitting and pressure disintegration techniques during re-shaping works undertaken as part of the EPSP experiment highlighted a preference for pressure disintegration.

Wire sawing has been shown to be a feasible technique for construction of slots for the concrete dome component of deposition tunnel plugs during the DOMPLU experiment. This has included modification of the technique to utilise a push cutting action rather than a pull cutting action.

Similarly, wedging and grinding has been shown to be a feasible technique for construction of slots for the concrete wedge component of deposition tunnel plugs during the POPLU experiment. The application of this technique was particularly advantageous in the context of the ONKALO site, as it allowed construction to be undertaken without workers being located under unsupported rock.

#### 9.3.3 Bentonite Seals

For several plug and seal designs, bentonite components provide the primary sealing function. These include the reference drift and ILW vault seal in Andra's Cigéo repository, the plug design tested in the EPSP experiment, SKB's and Posiva's reference deposition tunnel plug, and the preliminary concept for shaft seals in Germany. For the DOPAS Project, Posiva decided not to implement a bentonite seal in the POPLU experiment in order to be able to evaluate the concrete wedge independent of the performance of a bentonite seal.

In the DOPAS Project, the technical feasibility of several different types of bentonite seals has been demonstrated:

- An admixture of bentonite pellets and crushed pellets has been successfully installed in the FSS experiment with an average density of 1,480 kg/m$^3$. Although this did not meet the original specification of 1,620 kg/m$^3$, re-evaluation of the performance of the bentonite admixture has indicated that the required swelling pressure of 5 MPa can be achieved with an admixture dry density of 1,500 kg/m$^3$. Significant learning regarding the emplacement of bentonite admixtures was achieved during the FSS experiment. This included, for example, the arrangement of the augers and the need for the conveyor arm to be designed to better fill the top of the tunnel. This latter development is considered to be readily achievable, although experimental testing will still be required. The achievement of suitable bentonite densities is considered to have been demonstrated in the FSS experiment.
- In the EPSP experiment, significant developments in the fabrication of pellets manufactured from Czech bentonite and their emplacement have been undertaken. This progress has enhanced the confidence that Czech bentonite can be utilised in the Czech repository in the future. The pellets have been successfully emplaced in the EPSP experiment and are beginning to swell in response to initial saturation of the experiment.
- In the DOMPLU experiment, design work has focused on implementation of bentonite zones that will reduce the swelling pressure acting on the concrete dome to a maximum of 2 MPa. Monitoring results available for this report tracked the initial development of swelling pressures up to a few hundred kilopascals, but full swelling pressure is yet to be reached.

Overall, the work on bentonite seals in the DOPAS Project has identified a range of designs that could be utilised in specific situations. In France, pellet-based systems are preferred, as they are judged to represent an efficient industrial method of emplacement, whereas in Sweden, bentonite seals based on pre-compacted blocks surrounded by pellets have been selected, as experience in placement of these materials is already available through work on the emplacement of deposition tunnel backfills. Systems of pre-compacted blocks surrounded by pellets are able to deliver bentonite seals with higher dry densities (the target density for the bentonite seal in the DOMPLU experiment is 1,700 kg/m$^3$), but these high densities are not required in clay host rock systems, such as the Callovo-Oxfordian Clay in which the Andra drift and ILW vault seal will be constructed.

#### 9.3.4 Concrete Walls

A wide range of concrete containment walls have been tested in the DOPAS Project experiments:

- In the FSS experiment, Andra tested two concrete containment walls, one constructed from SCC and another constructed from shotcrete.
- In the EPSP experiment, two glass-fibre-reinforced shotcrete plugs were constructed.
- In the DOMPLU experiment, an unreinforced concrete dome was constructed.
- In the POPLU experiment, a reinforced concrete wedge was constructed in two sections.

Work on concrete materials in the DOPAS Project has allowed the development of several concrete mixes with excellent properties for application in repository plugs and seals. The concretes include binary mixes of cement and silica fume (FSS SCC wall, EPSP and DOMPLU), a ternary mix of cement, silica fume and blast furnace slag (FSS shotcrete wall), and a ternary mix of cement, silica fume and fly ash (POPLU).

The concrete mixes incorporate a range of aggregates and additives to achieve the necessary properties and workability. The POPLU experiment has limited the use of polycarboxylate-based superplasticisers in favour of naphthalene-based products, which have a lower potential for radionuclide sorption (Andersson *et al*., 2008). Experience at all of the experiments has demonstrated the need for procedures to respond to quality control measurement of concrete properties prior to application, for example the ability to add additional superplasticiser to meet slump flow requirements and the need for appropriate temperature control prior to, and during, emplacement.

All of the concrete mixtures were designed so that the concrete leachate waters would have a reduced pH. The EPSP concrete mix represents an intermediate stage in the development of low-pH shotcretes in the Czech Republic and has a pH of approximately 11.4. The pH of leachate water generated from the concretes used in FSS, DOMPLU and POPLU was less than 11.

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. This performance demonstrates the suitability of the mixes for application in repositories.

Evaluation of the performance of the concrete mixes at full-scale has demonstrated good scalability of concrete properties, although some differences to the expected properties have been noticed, e.g. the shrinkage of the B200 concrete used in the DOMPLU experiment was lower than expected.

Many lessons have been learnt during the DOPAS Project regarding the emplacement of concrete materials. SCC has been used successfully in FSS, DOMPLU and POPLU[11], but requires the erection and subsequent removal of formwork, which must be factored into the operational schedule if SCC is used in the repository. In contrast, shotcrete walls can be

[11] The POPLU concrete was self-levelling, but its slump flow measurement was not consistent with it being classified as SCC.

emplaced rapidly without the need for additional structures, but emplacement of shotcrete is dependent on operator skill and can be affected by rebound leading to variable properties throughout the walls. The experiences of the FSS and EPSP experiments with regards to shotcrete were quite different, partly as a result of the type of cements used in FSS, 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.

The use of reinforcement as part of SCC structures has the benefit that it can also act as a protection for workers against rock fall during installation work, but has the drawback that it can complicate the installation procedure (in terms of both space and time) compared to constructing SCC structures without reinforcement (although removal of reinforcement from SCC structure design must be compensated for in the design). The use of relatively dense reinforcement in parts of the POPLU concrete wedge required the modification of the concrete mix (change of aggregate size) to ensure flowability. The mock-ups proved beneficial for addressing the concrete mix and thus improvements were made prior to emplacement.

#### 9.3.5 The Plug/Seal-Rock Interface

The plug/seal-rock interface, including the EDZ, can be a critical part of a plug/seal with respect to its hydraulic performance. This is particularly the case for the interface between concrete components and the rock, where gaps may occur as a result of the emplacement process, or owing to shrinkage/displacement of the concrete following emplacement. For these concrete components, contact grouting is required to close the gaps formed by these processes. In the DOPAS Project, methods to facilitate concrete grouting have been tested, including release of the DOMPLU concrete dome using an innovative cooling system. In both the EPSP and POPLU experiments, contact grouting has been undertaken as a staged process with the success of initial grouting campaigns tested by initial pressurisation of the plug. The results of the pressurisation have indicated that subsequent re-grouting should focus on the rock for the EPSP experiment and should focus on the concrete wedge-rock interface for the POPLU experiment.

The DOPAS Project has also tested specific grouting procedures, with preliminary grouting of the outer regions of the plug/seal-rock interface at relatively low pressures followed by higher pressure grouting of central sections of the interface.

In addition to contact grouting, POPLU has demonstrated in mock-up tests and the plug itself the potential additional benefits of bentonite tapes for sealing of the interface between the concrete wedge and the rock. This goes beyond the tape’s primary function of providing confinement for the grouting paths. Monitoring of the early stages of pressurisation of the POPLU experiment is being undertaken and confirmation of the bentonite tapes performance has yet to be established.

A particular issue addressed by the FSS experiment is the filling of potential break-outs in the argillaceous host rock of the Cigéo repository. Work during the mock-up tests evaluating bentonite emplacement has developed the techniques that will be used to ensure the filling of these parts of drift and ILW vault seals. These developments include reductions in the breakages of the bentonite pellets and changes to the physical arrangements of the screw augers.

In the German programme, the development of bitumen-based sealing elements has included testing of the sealing of the EDZ using highly mobile bitumen, and has demonstrated that the bitumen infiltrates the EDZ, including fractures with an aperture of ~20 µm.

### 9.3.6 Filters

In the DOPAS Project, porous filters (and the pressurisation chamber in EPSP) have been used to rapidly pressurise the experiments to test the performance of the plug/seal structures in response to saturation of the underground following emplacement of (parts of) the EBS. The pressurisation of the experiments has worked well, and has allowed the experiments to be controlled and experimental pressurisation plans to be adapted based on the results of monitoring.

In the repository, and also in the experiments, filters are used to control the pressures acting on concrete structures, in particular to ensure that pressures are low during concrete curing, and that saturation and pressurisation of components of plugs and seals is applied homogeneously.

Filters are generally considered for application in plug/seal systems in crystalline rocks, where groundwater flow may be higher than in clay and salt host rocks, and, in particular, may be focused on water conducting fractures. The need for filters prior to the closure of the access tunnels in repositories developed in crystalline rocks may depend to a degree on site-specific factors, such as the hydraulic conductivity of host rocks with a sparse fracture system and water flows in the location of plugs and seals. However, the presence of filters provides the ability to control plug/seal performance during the later stages of repository evolution (whole lifetime after installation) and adds robustness to plug/seal design. Therefore, it is expected that, based on the experiences of the design and performance of filters in the DOPAS Project, filters would form part of plug/seal designs in the repository.

### 9.3.7 Temporary Structures

The full-scale experiments in the DOPAS Project have illustrated the importance of temporary structures in the overall feasibility of installation and performance of plugs/seals. Temporary structures are used to facilitate emplacement and include the delimiters between the main functional components and the formwork used for pouring SCC[12].

The temporary structures designed and utilised in the DOPAS Project full-scale experiments have performed well. In particular, the formwork designs used for the DOMPLU and POPLU experiments have been successfully implemented. No disruption to the rock was caused by the POPLU formwork within the one-metre safety distance in front of the plug (towards the central tunnel). A bracing frame attached to the rock by rock bolts was used to support the formwork.

The DOPAS Project full-scale experiments have also demonstrated the successful use of different types of delimiters for supporting the installation of plug/seal components. These include the LECA® beams and geotextile materials tested in the DOMPLU experiment.

### 9.3.8 Monitoring Systems

The full-scale experiments undertaken in the DOPAS Project have utilised a range of sensors to monitor a series of common parameters, for example:

- Temperature.
- Total pressure and pore pressure.
- Strain and displacement.

[12] These structures are referred to herein as "temporary" structures as their function is only to temporarily support other components on the plug/seal system during installation.

- 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. Wireless monitoring 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 as discussed in Section 9.2.1.

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 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 plugs and seals in the repository is feasible and might produce relevant data. For example, monitoring of the pressure inside filters can be used to understand the development of stress acting on retaining walls, and monitoring of leakage rates can be used to evaluate the performance of plugs in the short-term against watertightness-related safety functions.

Further evaluation and comparison of the monitoring systems used in the DOPAS Project is provided in the DOPAS Project Final Summary report (DOPAS, 2016d).

## 9.4 Operational Issues Resolved in the DOPAS Project

The DOPAS Project has addressed a large number of operational issues associated with the construction of plugs and seals. The achievements in the DOPAS Project with respect to these issues are summarised below.

### 9.4.1 Health and Safety during Plug and Seal Construction

The DOPAS Project has addressed several issues associated with health and safety during the construction of plugs and seals. In particular, the practical experience of constructing plugs/seals at full-scale has allowed experience to be gained in the hazards posed by working in restricted spaces, sometimes with multiple individuals performing separate tasks.

Consideration of safety during construction and installation is paramount and provides an important constraint on design and operational schedules. For plugs and seals, protecting workers against the potential for rockfall has a significant impact on design. An example is the reduced length of drift support that can be removed from the location of Andra’s drift and ILW vault seals compared to shaft and ramp seal, owing to the relatively lower competency of the Callovo-Oxfordian Clay host rock in the location of the seals.

For the POPLU experiment, initial plans to use wire sawing to construct the wedge were revised based on a review of operational safety that identified concerns with the various approaches that were initially proposed and then deemed unsuitable for worker safety protection. This led to a re-evaluation of the slot excavation method and the redesign of the concrete reinforcement so that it also acted as a protection for the workers (for example, workers installing the monitoring system). On the other hand, the protection of workers proposed for the design of the wire sawing process used for the excavation of the DOMPLU niche was deemed to be acceptable for application in the Äspö HRL. Testing two different excavation methods for the plug slot will enable the methods to be compared and contrasted; this also gives the additional benefit that either method can potentially be used in the future repository.

Another lesson learned from the conduct of the DOPAS experiments is the management of dust during the installation of plugs and seals, especially the management of dust created during the installation of bentonite powder (in FSS), and shotclay and shotcrete (in EPSP). Dust generation can be mitigated through the use of enclosed bentonite conveyance methods and by water spraying during installation.

#### 9.4.2 Logistical Issues Associated with Plug and Seal Construction

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

#### 9.4.3 Project Management during Plug and Seal Construction

The DOPAS Project has illustrated some of the complexity that will need to be addressed during the industrialisation of plug/seal construction and installation activities during repository operations. The installation of plugs and seals requires many activities, and, therefore, there is a need to develop simple and repetitive commissioning methods. Much of the work in the DOPAS Project has been of a "one-off" nature, but this experience has been useful to identify where routine application of methods can be undertaken.

Experiences gained during discussions with stakeholders, particularly with the regulator for the case of Posiva and the POPLU experiment, have provided valuable insight into the technical and safety questions that can arise during full-scale *in-situ* demonstrations.

The DOPAS Project has also demonstrated good practice in acceptance procedures to be employed during repository operation. This includes, for example, Posiva's methods of foreign materials review, which ensures repository site preservation.

# 10 Remaining Technical and Operational Issues

This chapter discusses the remaining technical and operational issues that need to be addressed prior to, or during, the implementation of plugs and seals during repository operation. This issues discussed are those that have been identified to date; further issues may be identified in the future. The structure of the discussion mirrors that used to discuss the progress in the DOPAS Project in Chapter 9:

- In Section 10.1, remaining issues associated with the application of systems engineering approaches during the DOPAS Project is discussed.
- In Section 10.2, further demonstration of plug and seals safety functions is discussed.
- Section 10.3 discusses remaining work on technical issues associated with plugs and seals.
- Section 10.4 discusses remaining work on operational issues associated with industrialisation of plugs and seals construction.

The DOPAS Project has considered the further development of plug and seal reference designs at different stages of development, and has included experiments on plugs and seals with different levels of ambition. The full evaluation of the experiments is outstanding, and for EPSP, DOMPLU and POPLU will involve further monitoring of the experiments beyond the completion of the DOPAS Project. This discussion is focused on the long-term resolution of technical and operational issues in preparation for finalising the designs of plugs and seals in conjunction with the start of repository operations.

## 10.1 Further Development of Systems Engineering Approaches in Repository Design

In the DOPAS Project, the design bases for plugs and seals were initially collated using a bottom-up process without the application of strict definitions of the requirements and conditions to be included at each level in the hierarchy (see Chapter 3 and DOPAS, 2016a, for further details on the hierarchy). This allowed identification of a hierarchical structure applicable to all of the plugs and seals considered in the project, and its application in the evaluation of experiment performance. The work has illustrated that requirements can be structured into a common hierarchy that is developed in parallel with the development of designs. 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.

In addition, the work on requirements, although focused on plugs and seals, is thought to be generic, i.e. the DOPAS Design Basis Workflow (Figure 3.1) could be applied to the development of design bases for all elements of the multi-barrier system and to the components of each of the sub-systems. However, it must be recognised that development of comprehensive design bases in formalised hierarchies containing all of the links between the requirements is a highly-intensive process. Parallels could be drawn with the development of databases of features, events and processes to underpin safety assessment models; although the development of these databases was originally viewed as a method for defining the scope of assessment models, their use is now more widely applied to cross-checking the completeness of the models. Similarly, further application of systems engineering principles in repository programmes may lead to the conclusion that requirements hierarchies are best applied in cross-checking of design specifications rather than in their development.

This raises the question of what level of detail is required in a design basis. Several of the design bases included in the DOPAS Project referred to standards, codes of practice or other control programmes. General reference to other more detailed procedures helps to keep design bases manageable, but visibility of some of requirements may be lost. Therefore, a process (or argument) is needed as a basis for the inclusion of requirements (and conditions) in a design basis. Four reasons for including a requirement in a design basis are proposed:

- Supports licensing, the traceability of decisions, and demonstration that the design meets the necessary safety performance requirements.
- Supports development of a construction contract / tendering process.
- Supports demonstration of construction feasibility and by this provides the WMO with confidence in approach adopted.
- Has direct impact or relationship to operational safety.

This identifies three audiences for a design basis: regulators, contractors and the WMO, and may help to guide the level of information required in a design basis as they are further developed in the future.

Further work on the use of systems engineering in repository programmes could also consider the following questions:

- How will the work on full-scale testing be used to develop design bases and construction procedures that can be followed in the repository?
- How can requirements-based design be developed from a research activity to a process used to manage the industrial implementation of geological disposal?

Reference designs can be modified in response to the results of the DOPAS experiments and supporting research – the modification of the reference designs is an important step in the application of the results of the DOPAS Project in each WMO programme.

Finally, extension of the systems engineering work undertaken in the DOPAS Project should give greater consideration to a broader range of requirements. The work in the DOPAS Project has concentrated on safety functions and design specifications linked to these safety functions (e.g. hydraulic conductivity and strain of concrete structures). Other requirements such as reliability and reproducibility, requirements on operational safety and operational constraints (logistics) and on the environment in which plugs and seals are constructed will need greater consideration going forward.

## 10.2 Further Demonstration that Designs Meet Safety Functions

As discussed in Section 9.2, the DOPAS experiments have provided good evidence that the designs tested are expected to meet the safety functions assigned to them, both in terms of qualitative and quantitative consideration of performance compared to the safety functions themselves, and in terms of quantitative evaluation of the performance of the experiments with respect to design specifications linked to safety functions.

However, the compliance evaluation reflects the current observations; additional analysis of the compliance is still ongoing and it is expected that further information from dismantling of the experiments and from long-term performance calculations will assist in assessing the compliance of the designs to the safety functions.

Going forward, the work undertaken in the DOPAS Project will have to be considered alongside other research activities to identify revised reference designs for plugs and seals, and compliance of these revised designs against the design basis will be required. This will include application of the experimental results in further modelling (for example to re-calibrate initial models if necessary) during more detailed design phases. This can follow and utilise the compliance assessment and performance evaluation approaches used in this report.

## 10.3 Remaining Technical Issues

### 10.3.1 Siting of Plug/Seal Locations

Application of siting methodologies for locating the specific positions of plugs and seals was largely successful in the DOPAS Project and allowed the plugs and seals to be constructed consistent with requirements. However, challenges were encountered. For example, one of the faces of the slot for the concrete dome in the DOMPLU experiment intersected a water-bearing fracture that was not expected as a result of the preliminary investigation of the niche selected for the experiment. Therefore, there may have to be further developments to the procedure used for preliminary characterisation of deposition tunnels, or the requirements or the plug design may have to be modified to allow for the potential for unexpected water conducting fractures. This procedure will have to be specific to the Forsmark site, where ground conditions are different to the Äspö HRL, and will also need to consider the combined performance of the plug and the deposition tunnel backfill.

The DOPAS Project has highlighted the need for further development of requirement statements related to the EDZ in the location of plugs and seals. In some requirements management systems, e.g. Posiva's VAHA system, requirements on the EDZ are currently expressed in terms of the EDZ not being continuous along the plug length, but this requirement is difficult to meet, owing to the lack of rock characterisation techniques that could be applied to show compliance. Requirements on the smoothness and tolerances of the plug slot surface are required, and these should reflect a range of structural designs. For instance, there was a significant impact on the experiment schedules as a result of the requirements on rock surfaces allowed for the DOMPLU and POPLU experiments respectively, which impacted on the use of wire-sawing or the wedging and grinding method.

### 10.3.2 Excavation of Plug/Seal Locations

Wire sawing, and wedging and grinding have both been shown to be feasible techniques for construction of specific parts of plugs and seals. However, these techniques require further refinement before they can be applied in the repository, and before a comparison of their costs and logistical aspects can be undertaken.

For wire sawing, several of the cuts had unwanted deviations, and further development of the technique is required with respect to the *in situ* stress conditions at repository sites (e.g. Forsmark), which may be higher than those at the Äspö HRL where the technique was demonstrated during the DOPAS Project. Wire sawing introduces hazards, especially when large sections of rock are removed from the tunnel ceiling section. Mitigation of these hazards may need further attention for wide-scale implementation of the technique (at least in Finland).

For wedging and grinding, an improved method for controlling the depth of the measurement holes used to control the wedging process is required, and logistical issues with the availability of grinding machines and the scheduling of their routine maintenance need to be addressed.

### 10.3.3 Bentonite Seals

The use of pre-compacted blocks and powder-based admixtures have both been demonstrated as suitable physical forms for bentonite used to provide low hydraulic conductivities in plugs and seals.  In all experiments undertaken in the DOPAS Project, challenges have been encountered when installing bentonite materials close to the roof of tunnels, and specialised routines for filling these parts are required.  Although required bentonite densities have been achieved by the installation procedures applied in the DOPAS Project experiments, there has been (sometimes significant) spatial variability in emplaced dry density of bentonite, and requirements on emplaced density and/or further understanding of homogenisation processes are needed as disposal programmes move forward.

### 10.3.4 Concrete Walls

As discussed in Section 9.3.4, a range of low-pH concrete mixes have been developed and successfully tested in the DOPAS Project.  The results from the DOPAS experiments have demonstrated that SCC mixes that meet design specifications are available for application in the repository, but shotcrete mixes require further work (e.g. to reduce pH of the leachate water or to reduce the incidence of rebound).  Nonetheless, further development of shotcrete mixes may benefit some programmes, as shotcreting can, in some circumstances, be employed relatively easily (e.g. without the need for formwork).

Further work on concrete walls also requires the development of optimised delivery routines and other logistical issues that fully consider the full range of operational activities occurring in the repository at the time of delivery, and, for some programmes, elaboration of the acceptance criteria to be applied during repository operation.

### 10.3.5 The Plug/Seal-Rock Interface

The experiences from the DOPAS experiments have shown that grouting of the plug/seal-rock interface is a critical step in the successful implementation of plugs and seals.  Further research and development is needed into grout materials and procedures (including quality control methods and mock-up demonstrations) for their emplacement in a range of host rocks to reduce the risk that re-grouting of the plug/seal-rock interface would be required.

In addition to contact grouting, the DOPAS Project has also demonstrated that grouting to improve ground conditions may be required for some plugs and seals.

### 10.3.6 Filters

A range of filters have been successfully applied in the EPSP, DOMPLU and POPLU experiments, and few problems have been encountered. Remaining work on filters therefore relates to the optimisation of filter designs, including material selection and final dimensioning in parallel with revisions to other components in reference plug/seal designs.

### 10.3.7 Temporary Structures

Temporary structures include the delimiters used to separate and support installation of plug/seal components, and the formwork against which SCC is poured.  All of the temporary structures have performed well in the DOPAS Project experiments.  The testing of LECA® beams and geotextile materials in the DOMPLU experiment was successful demonstrating that these materials could be used in a repository.  Further work on temporary structures is mainly focused on developing the final detailed and optimised designs.  For example, whereas POPLU used blocks that were dimensioned with respect to available moulds, the final design will be optimised.

### 10.3.8 Monitoring Systems

Relatively detailed monitoring systems have been used to track the performance of the DOPAS experiments and to demonstrate consistency with requirements. The impact on the results of such extensive monitoring can only be fully assessed after dismantling of the experiments, but some influence of the monitoring systems on the experiment results has already been noted (for example, the tightness of lead-throughs has been a problem in some of the tests). 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 large numbers of monitoring sensors 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. Further development of wireless monitoring systems would also be beneficial with respect to application in future full-scale experiments and commissioning tests.

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

## 10.4 Industrialisation of Plugging and Sealing

As discussed above, the DOPAS Project has contributed towards demonstration of the technical feasibility of plugs and seals. However, the results of the experiments need to be used in the development of industrial solutions for installing many tens to hundreds of plugs and seals in each repository constructed. Industrialisation requires collation of construction procedures and quality control procedures that can be used to safely construct plugs and seals with reproducible structures, high reliability and acceptable costs. These procedures will need to be adapted to site-specific geological conditions and the space available underground.

Industrialisation will require the transfer of the lessons from the full-scale DOPAS experiments to the repository. This may involve further full-scale testing of revised reference designs in the repository to demonstrate compliance of the final design prior to award of an operation licence. Industrialisation also needs to consider the availability of construction materials in the future (i.e. decades later), the instrumentation required to directly monitor plug/seal behaviour, and how these data will be used in future decision making.

Dimensioning of all related facilities based on practical experiences and available equipment is one important part of future work of all WMOs. It is important to study the whole operation sequence. This is one learning point from DOPAS experiences as well.

Future work requirements also include the potential adaption/up-scaling that is required to implement the sealing solutions studied to an operational repository. This includes both technical and economic appraisal, considering aspects such as manufacturing considerations, construction methodologies including deployment (remote or man access), testing and verification, programme duration, manpower and costs.

# 11 Conclusions

WP2, WP3 and WP4 of the DOPAS Project have included:

- Collation of the design basis for the plugs and seals considered in the DOPAS Project, conceptual and basic designs, and the strategy adopted in programmes for demonstrating compliance of the designs with the design bases.
- Detailed design, site selection and characterisation, and construction of the experiments.
- Evaluation of the performance of the full-scale experiments and evaluation of the conclusions from the experiments conducted in the DOPAS Project with respect to the technical feasibility of constructing the reference designs.

The experimental work undertaken in the DOPAS Project has been largely successful. By the time of the freeze date for this report, 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 and after dismantling. 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 the results are consistent with the design basis. Additional analysis of the compliance is still ongoing and experiment dismantling and long-term assessment calculations will also be used to assess the compliance of the designs to the safety functions and design specifications.

In the evaluation of the DOPAS experiments undertaken within the scope of the DOPAS Project, there has been a focus on key design specifications, which 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 discussed in this report. On-going evaluation of the experiments undertaken within the DOPAS Project will be carried out by WMOs following the completion of the DOPAS Project, and will consider the full range of issues collated in the design basis.

As a result of the German experimental work, existing seal types consisting of MgO or salt concrete could be improved, and new seal types based on the use of bitumen and on a mixture of crushed salt and fine clay were developed.

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.

The achievements in the DOPAS Project include the following:

- Development of a structured approach to requirements hierarchies, including the use of these hierarchies as a basis for compliance assessment, that are 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.
- Development and application of techniques for siting repository plugs and seals.
- Application and assessment of techniques for construction of plug/seal slots to high specifications.

- 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 tapes, and use of highly-mobile bitumen to seal the plug/seal-rock interface in anhydrites.
- Demonstration of the application of filters, delimiters and formwork to aid the installation of plugs and seals.
- Adequate monitoring of the performance of plugs and seals using existing monitoring technologies.
- Addressing concerns regarding health and safety by modifying proposed approaches to plug slot excavation.
- Addressing issues with logistics and project management to successfully construct plugs and seals within the timeframe of the Project.

In addition, the work in the 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 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.

## 12 References

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

Andra (2013). The Cigéo Project. Meuse/Haute-Marne Reversible Geological Disposal Facility for Radioactive Waste. Project Owner File 504VA – DCOM/13-0271, Public Debate of 15 May to 15 October 2013.

Auld, F.A. (1996). Design of Underground Plugs, Chapter 10 in Sealing of Boreholes and Underground Excavations in Rock, pp 225-266, edited by Fuenkajorn, J. and Daemen, J.J.K., Chapman and Hall, London, 1996.

BMU (2010). Federal Ministry for the Environment, Nature Conservation and Nuclear Safety: Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste. Version of Sept., 30. 2010.

Börgesson L., Sandén T., Andersson L., Johannesson L-E., Goudarzi R. and Åkesson M. (2015). End plug for Deposition Tunnels – Preparatory Modelling and Tests of the Sealing and Draining Components. SKB R-Report, R-14-25.

Bosgiraud, J.-M. and Foin, R. (2013). FSS Tunnel Model Design Report. DOPAS Work Package 3, Deliverable D3.2, Version A, 21.

Carter, D.E. and Baker, B.S. (1992). Concurrent Engineering: The Product Development Environment for the 1990s. Addison-Wesley Publishing Co., Inc., Reading, MA.

Conil, N., Talandier, J., Noiret, A., Armand, G. and Bosgiraud, J-M. (2015). DOPAS Work Package 4, Deliverable D4.2. Report on Bentonite Saturation Test (REM), Version B, August 2015.

Czaikowski, O. and Wieczorek, K. (2016). DOPAS Work Package 3, Deliverable D3.31. Final technical report on ELSA related testing on mechanical-hydraulical behaviour - LASA, 29 February 2016.

DAfStb (2004). Deutscher Ausschuss für Stahlbeton: Betonbau beim Umgang mit wassergefährdenden Stoffen Teil 1: Grundlagen, Bemessung und Konstruktion unbeschichteter Betonbauten, Berlin.

DIN EN (1990). Grundlagen der Tragwerksplanung. Eurocode 0: DIN EN 1990: Grundlagen der Trag-werksplanung(Deutsche Fassung EN 1990:2002 + A1:2005 + A1:2005/AC:2010).

DOPAS (2012). Technical Feasibility and Long-term Performance of Repository Components – Full-scale Demonstration of Plugs and Seals. Grant Agreement for Collaborative Project, Annex I – "Description of Work". Grant Agreement 323273, Version date 26 October 2012.

DOPAS (2016a). WP2 Final Report: Design Basis for DOPAS Plugs and Seals. DOPAS Work Package 2, Deliverable D2.4, Version 1.

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

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

DOPAS (2016d). DOPAS Final Project Summary Report. DOPAS Work Package 6, Deliverable D6.4. DOPAS Project Deliverable D6.4.

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

Engelhardt, H.J., Jobmann, M., Müller-Hoeppe, N. (2011). Materialspezifikation für Dichtelemente für die Planung von Schacht- und Streckenverschlüssen. Arbeitspaket 9.1.2, Vorläufige Sicherheitsanalyse für den Standort Gorleben, Rev01, DBE TECHNOLOGY GmbH: Peine, 24.08.2011.

Eurocode 2 (2008). SS-EN 1992-1-1:2005: Eurocode 2: Design of Concrete Structures – Part 1-1: General Rules And Rules For Buildings, Swedish Standard Institute, Stockholm.

Forsberg, K., and Mooz, H. (1991). The Relationship of System Engineering to the Project Cycle, Center for Systems Management, 5333 Betsy Ross Dr., Santa Clara, CA 95054; also available in A Commitment to Success, Proceedings of the First Annual Meeting of the National Council for Systems Engineering and the 12th Annual Meeting of the American Society for Engineering Management, Chattanooga, TN, 20-23 October 1991.

García-Siñeriz, J.L., Alonso, M.C. and Alonso, J. (2008). Application of Low pH Concrete in the Construction and the Operation of Underground Repositories. Proceedings of the Euradwaste '08 Conference.

Glaubach, U., Hofmann, M., Gruner, M., Königer, F., Emmerich, K., Schuhmann, R., Grafe, F. & Wilsnack, T. (2016). Teilbericht zum Arbeitspaket 4: Halbtechnische Versuche zu den Arbeitsschritten 2.1 bis 2.6 Im Rahmen des Vorhabens „Schachtverschlüsse für Endlager für hochradioaktive Abfälle“ ELSA-Phase 2: Konzeptentwicklung für Schachtverschlüsse und Test von Funktionselementen von Schachtverschlüssen, Technische Universität Bergakademie Freiberg, Institut für Bergbau und Spezialtiefbau (in German).

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

Grahm, P. and Karlzén, R. (2015). System design of Dome Plug. Experiences from full-scale wire sawing of a slot abutment for the KBS-3V deposition tunnel plug. SKB Report R-14-24.

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

Hakola, I., Halonen, M., Bohner, E. (2014). Test plan for the Full-scale Test Including the Instrumentation Plan for POPLU Plug. DOPAS Work Package 3, Deliverable D3.25.

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

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

Holt, E. (2014). POPLU Concrete Test Memorandum Concrete Mix Design and Performance Study. DOPAS Work Package 3, Deliverable D3.27. Version 1, 28 February 2014.

Holt, E. and Dunder, J. (2014). Detailed Design of POPLU Deposition Tunnel End Plug. DOPAS Work Package 3, Deliverable D3.24.

Holt, E and Koho, P. (2016). POPLU Experiment Summary Report. DOPAS Work Package 4, Deliverable D4.5.

Holt, E., Bohner, E., Sandén, T., Malm, R., Pacovský, J. and Svoboda, J. (2016b). Instrumentation and Monitoring Systems for Evaluation of Plug Responses in Geological Disposal Demonstrations. In: Proceedings of the DOPAS 2016 Seminar.

Hunsche, U., Schulze, O., Walter, F., Plischke (2003). Projekt Gorleben, Thermomechanisches Verhalten von Steinsalz, Abschlussbericht (9G2138110000). BGR Hannover.

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

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

IAEA (2011a). Disposal of Radioactive Waste. IAEA Safety Standards Series No. SSR-5, IAEA, Vienna.

IAEA (2011b). Geological Disposal Facilities for Radioactive Waste Specific Safety Guide. IAEA Safety Standards Series No. SSG-14, IAEA, Vienna.

Jantschik, K. and Moog, H. (2016). DOPAS Work Package 3, Deliverable D3.29. Final technical report on ELSA related testing on chemical-hydraulical behaviour – LAVA, 29 February 2016.

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

Kelham, S. (1997). Effects of Cement Composition and Hydration Temperature on Volume Stability of Mortar," Proceedings of the 10th International Congress on the Chemistry of Cement, Vol 4, Paper 4iv060, Gothenburg, 1997.

Kosunen, P. (2014). URCF RSC Work Memorandum (POPLU). DOPAS Work Package 3 Deliverable D3.26.

Kronlöf, A. (2005). Injection Grout for Deep Repositories – Low pH Cementitious Grout for Large Fractures: Testing effect of superplasticizer on technical performance. VTT Building and Transport, Posiva working report 2005-08, 37 p.

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

Kudla, W., Gruner, M., Herold, P. & Jobmann, M. (2015). Schachtverschlusskonzepte für zukünftige Endlager für hochradioaktive Abfälle für die Wirtsgesteinsoptionen Steinsalz und Ton. Mining Report Glückauf 151 No. 1, Herne, Germany.

Magnusson J. and Mathern A. (2015). System Design of Dome Plug. Experience of Low-pH Concrete Mix B200. Material Properties from Laboratory Tests and Full-scale Castings. SKB Report P-14-26.

Malm, R. (2012). Low-pH Concrete Plug for Sealing the KBS-3V Deposition Tunnels. SKB Report R-11-04.

Müller-Hoeppe, N. (2010). Untersuchung der Kontaktzone am ASSE-Vordamm – Gesamtinterpretation, DBE TECHNOLOGY GmbH, Peine.

Müller-Hoeppe, N. and Eberth, S. (2009). ÜBERSICHT - Übertragung des Sicherheitsnachweiskonzeptes für ein Endlager im Salz auf andere Wirtsgesteine - Abschlussbericht, FZK02E9521, DBE TECHNOLOGY GmbH, Peine.

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

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

NASA (1995). Systems Engineering Handbook. SP-610S.

Noiret, A., Bethmont, S., Bosgiraud J-M. and Foin R. (2016a). DOPAS Work Package 4, Deliverable D4.8. FSS Experiment Summary Report, Version A, 3 August 2016.

Noiret, A., Bosgiraud J-M. and Foin R. (2016b).. DOPAS Work Package 4, Deliverable D4.1. FSS Experiment – Report on Qualification of Commissioning Methods, Version A, 12 August 2016.

Oreskes, N., Schrader-Frechette, K. and Belitz, K. (1994). Verification, validation and confirmation in numerical models in the earth sciences. Science, 263, 641-646.

Pescatore, C. (1995). Validation: the eluding definition. Radioactive Waste Management and Environmental Restoration, 20, 13-22.

Posiva (2012a). Design, Production and Initial State of the Underground Disposal Facility Closure. Posiva Report POSIVA 2012-19.

Posiva (2012b). Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto - Synthesis 2012. Posiva Report POSIVA 2012-12.

Posiva (2012c). YJH-2012. Nuclear Waste Management at Olkiluoto and Loviisa Power Plants: Review of Current Status and Future Plans for 2013-2015. Eurajoki, Finland: Posiva Oy, 370 p.

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

Raivio, P. and Hansen, J. (2007). Technical Performance of Cementitious Grouting Materials for ONKALO: Laboratory Tests 2006. Posiva Working Report 2007-78.

Ranta-Korpi, R., Karttunen, P. and Sievänen, U. (2007). R20 programme: Field Testing of Grouting Materials. Posiva Working Report 2007-102.

Rautioaho, E., Börgesson, L., L., Åkesson, M., Kristensson O., Valli, J., Hakala, M., Pintado, X. and Koskinen, K. (2016). Assessment of Watertightness and Mechanical Integrity of POPLU Plug. DOPAS Work Package 5, Deliverable D5.11.

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

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

SKB (2011). Long-term Safety for the Final Repository for Spent Nuclear Fuel at Forsmark. Main Report of the SR-Site project. SKB Technical Report TR-11-01.

SKB (2013). RD&D Programme 2013. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste. SKB Technical Report TR-13-18.

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

Svoboda, J., Hausmannová, L., Vašíček, R., Smutek, J., Stastka, J., Nádherná, D., Pacovská, D., Dvořáková, M., Hanusová, I., Belickova, L., Havlová, V., Večerník, P. and Trpkošová, D. (2016a). DOPAS Work Package 4, Deliverable D4.7. EPSP Experiment Summary Report.

Svoboda, J., Hausmannová, L., Vašíček, R., Smutek, J., Stastka, J., Nádherná, D., and Pacovská, D. (2016b). Monitoring Data Taken from the EPSP Plug Test Summary Report. DOPAS Work Package 4, Deliverable D4.6.

Trpkošová, D., Dobrev, D., Gondolli, J., Havlová, V. and Hokr, M. (2013). Methodology of Complex Safety Assessment of the Deep Repository. Final report, project no. FR-TI1/362. [Research report]. Řež u Prahy: ÚJV, 153 s. (in Czech).

Vašíček, R., Svoboda, J., Večerník, P. and Dvořáková, M. (2013). Testing Plan for EPSP Laboratory Experiment. DOPAS Work Package 3 Deliverable D3.16.

Vašíček, R., Levorová, M., Hausmannová, L., Šťástka, J., Večerník, P., Trpkošová, D. and Gondolli, J. (2014). Interim Results of EPSP Laboratory Testing. DOPAS Work Package 3 Deliverable D3.17.

Vašíček, R.; Hausmannová, L.; Šťástka, J.; Svoboda, J.; Nádherná, D.; Pacovská, D.; Hubálovská, J.; Večerník, P.; Trpkošová, D.; Gondolli, J.; Dvořáková, M.; Hanusová, I and Bělíčková, L. (2016). DOPAS Work Package 3, Deliverable D3.21. Final results of EPSP laboratory testing.

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

Wagner, K. (2005). Beitrag zur Bewertung der Sicherheit untertägiger Verschlussbauwerke im Salinargebirge, Dissertation an der TU Bergakademie Freiberg, Freiberg, Institut für Bergbau und Spezialtiefbau.

Weber, J.R., Keller, S., Mrugalla, S., Wolf, J., Buhmann, D., Mönig, J., Bollingerfehr, W., Krone, J. and Lommerzheim, A. (2011). Safety Strategy and Assessment for a German HLW Repository in Salt. *In*: Proceedings of the International High-level Radioactive Waste Management Conference (IHLWMC), 10-14.04.2011, Albuquerque, New Mexico.

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

Weetjens, E., Maes, N. and van Ravestyn, L. (2014). Model Validation based on *In Situ* Radionuclide Migration Tests in Boom Clay: Status of a Large-scale Migration Experiment, 24 Years after Injection. *In*: Norris, S., Bruno, J., Cathelineau, M., Delage, P., Fairhurst, C., Gaucher, E.C., Höhn, E.H., Kalinichev, A., Lalieux, P. and Sellin, P. (eds) Clays in Natural and Engineered Barriers for Radioactive Waste Confinement. Geological Society Publication 400, 613-623.

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

White, M.J. and Doudou, S. (2014). Designs of Reference Concepts and DOPAS Experiments: DOPAS Reference Designs Report. DOPAS Work Package 2, Deliverable D2.2, Version 1.1.

Zhang, C-L. (2016). DOPAS Work Package 3, Deliverable D3.32. Final report on the sealing behaviour of fractured claystone and seal materials (THM-Ton), 29 February 2016.