Nordic Full-Scale Demonstrations of Tunnel Plugging Technologies for Repository Conditions – 14282

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ABSTRACT

Two HLW deposition tunnel end plugs are being constructed in crystalline-rock in Finland and Sweden for deep geological repositories. These full-scale underground demonstrations are part of a Euratom demonstration project called DOPAS, which is running from 2012-2016 and involves 14 waste management and research organizations from 8 countries. The project goal is to improve the adequacy and consistency regarding industrial feasibility of plugs and seals to be used in different geological environments. The plug in Äspö, Sweden was constructed in early 2013 and the plug in ONKALO, Finland is scheduled for placement during the first half of 2014, with design, modeling and excavation now completed. New low-pH concrete plug materials have been developed and demonstrated for workability and durability properties. Elaborate monitoring systems have been designed using over 100 sensors to monitor each plug's performance during two accelerated pressurization tests. The expected mechanical and hydraulic performances of the plugs have been modeled during the design stage, and it is expected that the models will be updated based on the experimental results and reports generated in 2015-2016. The results will also be used to update reference designs and influence the plug requirements. All of these actions support long-term safety requirements, the future operation licensing process, and improving stakeholder confidence in repository operation. The published project outcomes can be used by the international community to enhance the siting, design, construction and quality management practices for future tunnel plugs and shaft seals used in various types of repository configurations and geological conditions.

INTRODUCTION

One major need identified by European nuclear waste management organizations prior to operation of HLW disposal facilities is the demonstration of tunnel sealing feasibility. In the year 2012 a project began, with joint funding from the Euratom's Seventh Framework Programme together with 14 European nuclear waste management and research organizations from eight countries. This four-year project, called DOPAS ("Full-Scale Demonstration Of Plugs And Seals") [1], is developing technologies for assessing tunnel plugging and sealing systems in varying geological disposal facilities for SNF and HLW. The project is built around a set of five full-scale plug demonstrations, together with laboratory experiments, modelling and performance assessment studies. The project is coordinated by Posiva Oy in Finland, who is host to one of the five experiments. The DOPAS requirements and design basis of plugs are managed by SKB in Sweden who also hosts one full-scale plug experiment.

BACKGROUND

Different types of plugs and other sealing structures are needed in HLW repositories worldwide, depending on the prevailing geological conditions. Part of these plugs serve to hydromechanically isolating different parts of the repository from each other, like deposition tunnel end plugs in the KBS-3 concept adopted for crystalline rock. The functional requirements of these plugs are mainly related to the buffer barrier and the risk for piping and erosion of its bentonite clay. Thus the plug system has to be watertight to stop or reduce the axial groundwater flow through a deposition tunnel and also be able to keep the backfill in its intended place. Furthermore, some plugs will have the role as a hydraulic seal to prevent the groundwater flow through the excavated access routes like tunnels and shafts in crystalline host rock. The controlling design parameters for the plugs are often related to the watertightness and durability over the plug's intended service life. Depending on the host rock geology, the purpose of the plug, and the long term safety functions of the plug, there are then different requirements and reference designs that are site specific. The plugs and seals will be used in a nuclear facility that set common challenges for developing the design basis, creating the designs, showing their compliance with the requirements and assessing the long term behavior and interactions with other barrier components and with the host rock.

European waste management organizations are at different stages of maturity in their repository development and in related licensing procedures for implementing geological disposal facilities. Construction license applications for SNF disposal facilities have been submitted in Finland and in Sweden, and construction of the facilities is foreseen to commence during this decade. In Sweden, the Äspö hard rock laboratory (HRL) has been operating since 1995 in the foreseen host rock environment of a future repository. In Olkiluoto, Finland, the ONKALO underground rock characterization facility (URCF), whose construction started in 2004, is foreseen to be licensed as part of Posiva's geological disposal facility for SNF.

The SKB dome plug experiment (DOMPLU) in the Äspö HRL and Posiva’s wedge plug experiment (POPLU) in the ONKALO URCF are demonstrating two types of deposition tunnel end plugs that could be utilized in crystalline-rock. Both plug types are intended to isolate the emplaced tunnel backfill, bentonite clay buffer and SNF canister from the central tunnels during the operation phase. These structural plugs are typically made of low-pH concrete and possibly reinforcing steel bars, with a design life in the range of 100 years. The development of construction materials for the plugs and seals meeting the repository requirements is included in the DOPAS experiments' work. Both demonstrations have the goal of constructing full-scale plugs and monitoring their performance when pressurizing them to the full dimensioning loads over a short (1-2 year) time scale to simulate 100 years of service life.

The difference in the Swedish and Finnish plug demonstrations is related to the amount and size of the filter and seal layers in the interface between the backfill clay and the concrete plug. The DOMPLU dome-plug design is intended for deposition tunnels where there may be higher levels of water inflow, while the POPLU design is intended as a concrete-alone test, without backfill sealing behind the plug.

METHODS

Defining Requirements

Both of these plug demonstrations aim, within the Euratom DOPAS project, to improve the knowledge about construction feasibility of the large sealing structures and given confidence in the industrial scale construction of such plug and seals to be used in different geological environments. The main project challenges are related to: 1) location selection and construction technologies underground, 2) new material development, 3) in-situ instrumentation and performance assessment, and 4) quality and safety assurance procedure development and implementation. Posiva’s experimental site will host the future disposal facility for SNF, thus setting stricter requirements on documentation, quality management procedures and selection of materials compared to other on-going experimental plugs. SKB's DOMPLU experiment strives, to the extent possible, to represent the future licensed design.

The deposition tunnel end plugs are a separate system part of the backfill design within the KBS-3V concept. The plugs have design requirements that are based on long-term performance and safety functions, as described within Posiva's Design Basis and Backfill Production Line 2012 reports [2, 3]. Examples of the most detailed design specific requirements for Posiva's future operational tunnel end plugs are:

- The plug shall maintain its hydraulic isolation capacity for at least 100 years.
- The mechanical strength of the plugs shall correspond to a pressure load of at least 7.5 MPa, including the ambient hydrostatic pressure.
- The main material component in the plug shall be quartz sand or crushed rock.
- The concrete shall be water tight after installation. The hydraulic conductivity of the concrete mass shall be <1x10-11 m/s.
- The cementitious materials that are used in plugs shall have a calcium to silica mass ratio less than 1:6.
- The organics and sulphur content in the plug shall be lower than 1 wt-%.

DOMPLU plug requirements in Sweden are similar, though some differences do exist such as material properties of the self-compacting concrete.

Due to the role of ONKALO in Posiva's future disposal facility, the POPLU experiment needs to comply with some oversight requirements of and reporting of the work to STUK, Finland's Radiation and Nuclear Safety Authority. The POPLU practices for information exchange procedures with the authorities and the procedures for various long-term safety and quality assurance approval (i.e. of stray materials and the requirements related to the classified nuclear safety related components) are important issues in addition to the construction and monitoring of the experiment.

Location Selection and Excavations

Location selection for the exact plug spot underground and the specific excavation methods of the plug location, have a limited record of previous full-scale testing, but they will be a part of the standard operations in future HLW disposal facilities. During the planning stage for excavation and location selection, the POPLU and DOMPLU projects have worked to develop practices related to occupational safety, selection of excavation methods such as wire sawing, and modified designs of tunnel supporting and rock support material use to preserve the geological conditions.

In Finland, the POPLU experiment is done in the demonstration area of ONKALO 420 meters below surface. Two plug demonstration tunnels were excavated in 2013, with tunnel lengths of approximately 26 meters and cross sectional area of 14.46 m^2 (4.35 meters high by 3.5 meters wide). Posiva's methodology of Rock Suitability Classification [4] was applied to characterize the fracture patterns, leakage and rock quality, prior to selecting the plug tunnel and the plug slot location within the tunnel. The final location and the minor fracture patterns are shown in Figure 1, where the yellow and red pattern represent a brittle deformation zone based on the detailed-scale model, dark grey lines show Tachymeter-measured traces of the largest fractures observed in the tunnel, and blue numbers indicate the length in meters from the central tunnel midpoint.

The POPLU plug slot excavation method will be decided upon based on discussions with contractors, cost, quality of excavation and safety. The plug construction is expected to take place during April to June 2014.

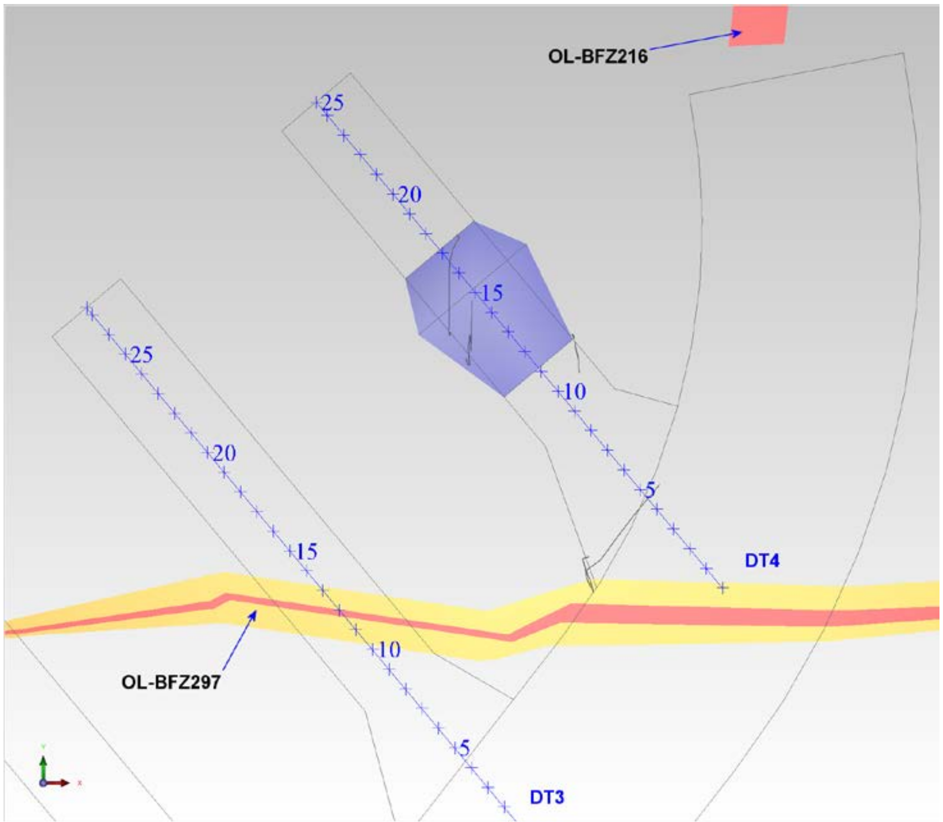

Fig. 1. Significant bedrock structures in ONKALO, in the vicinity of POPLU.

In Sweden, the DOMPLU experiment is carried out at 450 meters below surface in Äspö HRL, where conditions are similar to what will be the case in the SNF Repository in Forsmark. A suitable plug location was determined by core drilling and high pressure water injection tests (10 MPa) in a 30 meter long pilot hole. The test-tunnel was then excavated to 14 meters length by using drill and blast methods, with a modified blast sequence to ensure a minimal Excavation Damage Zone (EDZ). The contour boreholes were blasted in a separate round.

The tunnel dimensions correspond to the reference design of SKB`s deposition tunnels, which are 4,8 meters high by 4,2 meters wide, for a cross sectional area of 18,9 m^2.

The plug slot area was excavated to obtain smooth surfaces using the wire sawing technique in an octagonal shape (Figures 2-3).

The wire-sawing took longer than initially scheduled due to complications from rock stresses. As a consequence the originally planned pulling cuts were changed to blind cuts and accordingly a new drilling campaign was needed.

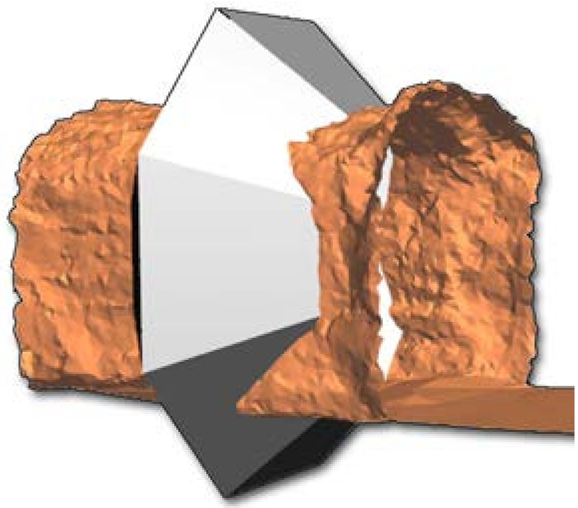

Fig 2. Model of the theoretical slot layout

Fig 3. The excavated slot for DOMPLU

RESULTS

Structural Designs

The POPLU plug will to be Posiva's first full-scale engineered barrier system (EBS) component constructed and demonstrated at the Olkiluoto disposal site. The original structural designs and calculations for Posiva's wedge plug were described by Haaramo et al [5] but were revised to the dome-shaped reference design within Posiva's Backfill Production Line report [2] to reflect experience gained in Sweden's earlier plug demonstrations [6, 7].

The POPLU wedge-shaped plug has dimensions of 6 meters in length and 5.5 meters diameter (Figure 4). The plug contains approximately 20 tons of steel reinforcement and the concrete will be cast in two sections, at approximately a two week interval. The rock grouting of the near-field will be done in three circumferential paths around the concrete, approximately three months after the concrete casting. Bentonite sealing tape will also be used in two bands between the plug and rock surface. A permeable filter layer is placed behind the plug to handle water during construction and operation, also during the accelerated pressurization test.

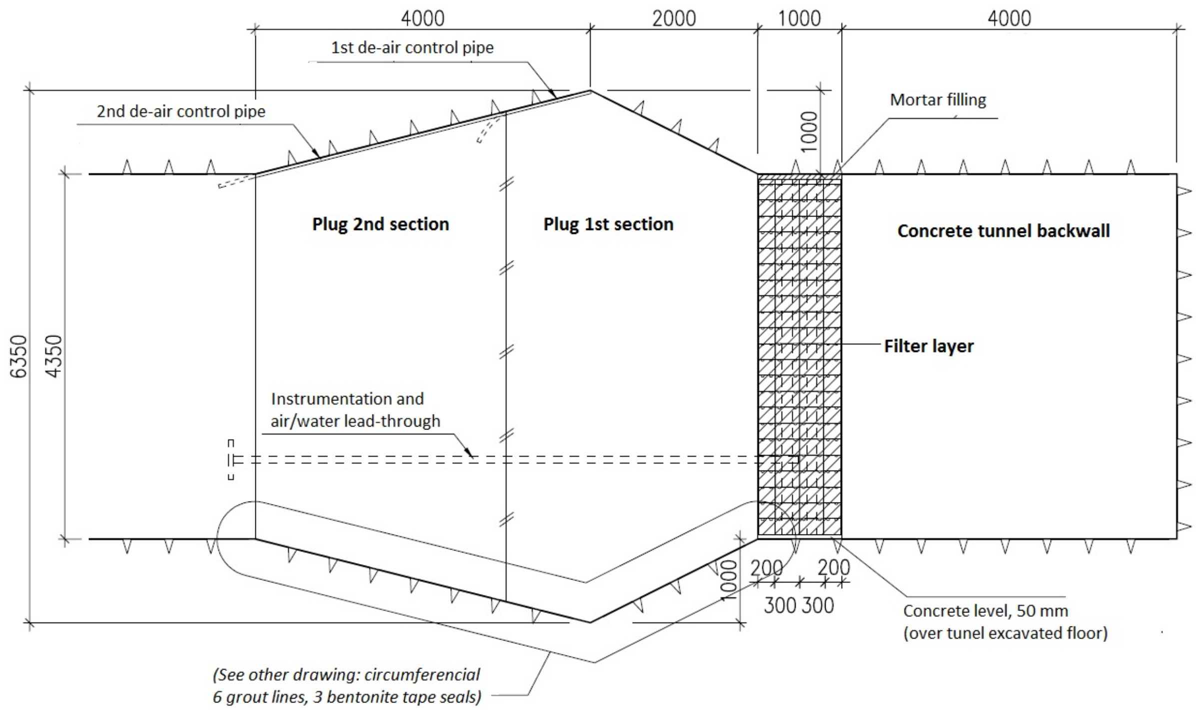

Fig. 4. Posiva's design for the POPLU (Wedge Plug) experiment, with filter layer shown at right.

Sweden's DOMPLU plug consists of an arched low-pH concrete dome, a bentonite seal, filter materials and delimiters, as shown in Figure 5. The design of the DOMPLU experiment was completed during 2011 and the plug was emplaced in March 2013. The low-pH concrete was not reinforced and was cast as one part. A cooling system was installed within the concrete to cool the structure down to +4°C at the time of casting to prevent thermal gradients. The cooling system was also activated later to force contraction and opening of the concrete-tunnel gap to facilitate grouting of the gap between the concrete and the rock contact. The contact grouting was done using ultrafine cement and took place at approximately three months after the casting.

In the DOMPLU design, many technical challenges were taken into account related to the practical implementation of plugs, including issues like the Excavation Damaged Zone (EDZ) in the tunnel; plug -backfill interactions with pressure conditions at repository depth; and smoothness of surfaces required for controlled concrete fitting.

A full-scale demonstration is vital to validate the underlying assumptions and the performed numerical simulations of the concrete dome. In addition, the functions of the filter and the bentonite seal will be thoroughly monitored and the water leakage through the plug will be determined under realistic conditions. As DOMPLU was designed and nearly finished in construction at the start of DOPAS project, the work of DOMPLU within the Euratom project is focused on the monitoring and performance assessment of the full-scale plug.

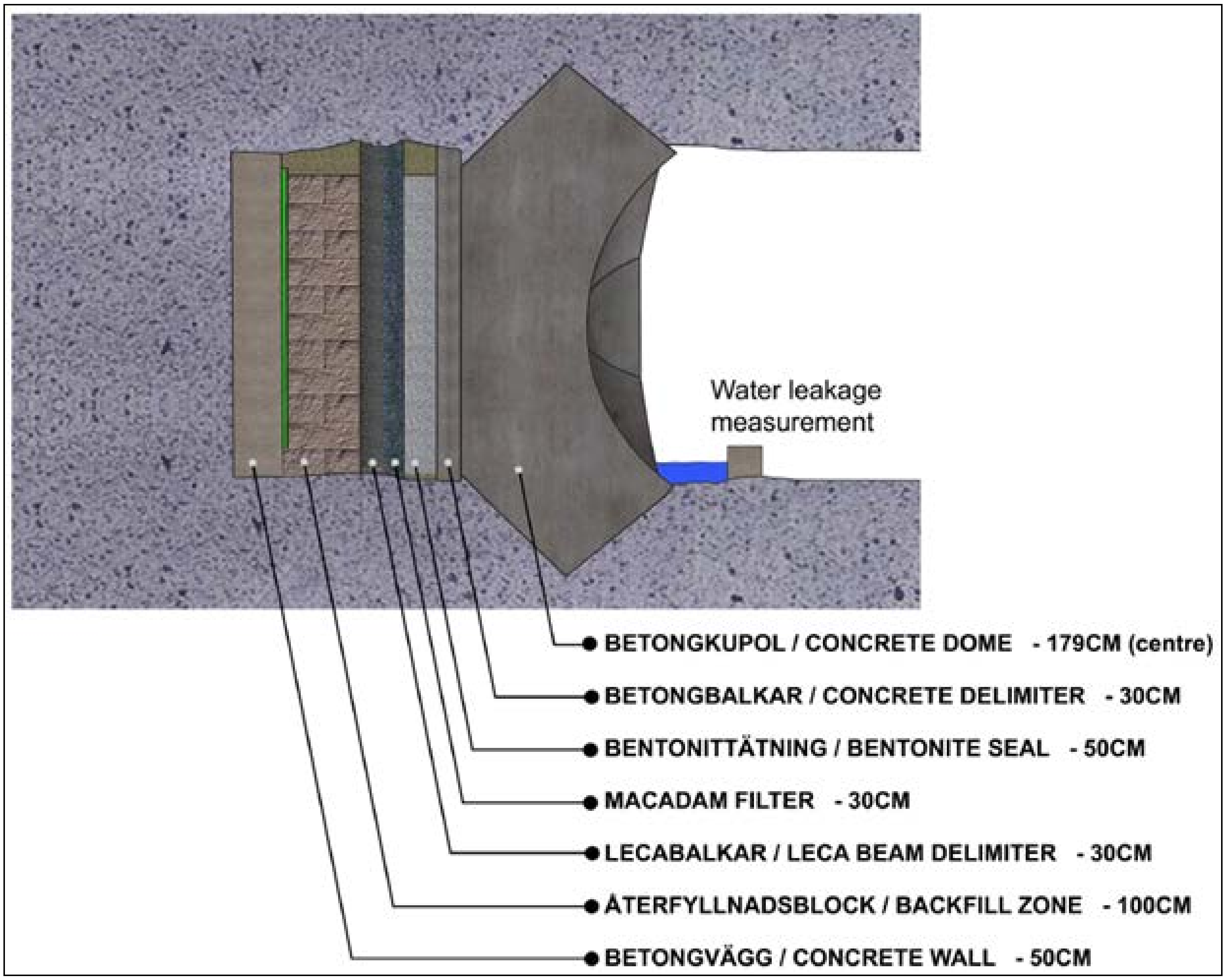

Fig 5. SKB's design for the DOMPLU experiment, with backfill, filter layers and bentonite seal on upstream side of the concrete dome. Water is collected by a tight weir downstream of the concrete dome and the leakage rate is continuously recorded by an on-line scale.

The full-scale demonstrations alone do not provide sufficient information on the performance of the plugs, and therefore modelling has been utilized and implemented in many stages of the design. Theoretical calculations have been done to ensure that the scope and target of the demonstrations are considered and the correct source data are provided for further analysis.

Mechanical, thermal and hydraulic models for the plugs have been developed to estimate the performance evolution over time. Initially, mathematical calculation have determined the stresses in the plug prior to the selection of the concrete grade and required reinforcement. The structure has then been modeled, i.e. with 4-to-8-node brick elements within a linear elastic material model, as shown graphically as displacement and stress plot for POPLU (Figure 6). In the event of an incomplete bond between concrete and rock, the magnitude of the horizontal displacement and the resulting compressive stress perpendicular to the surface in contact with the tunnel have also been estimated.

These various models will be validated and improved based on the monitoring results over the next couple of years and via the accelerated pressurization scenario. The results will be used to update future designs and requirements.

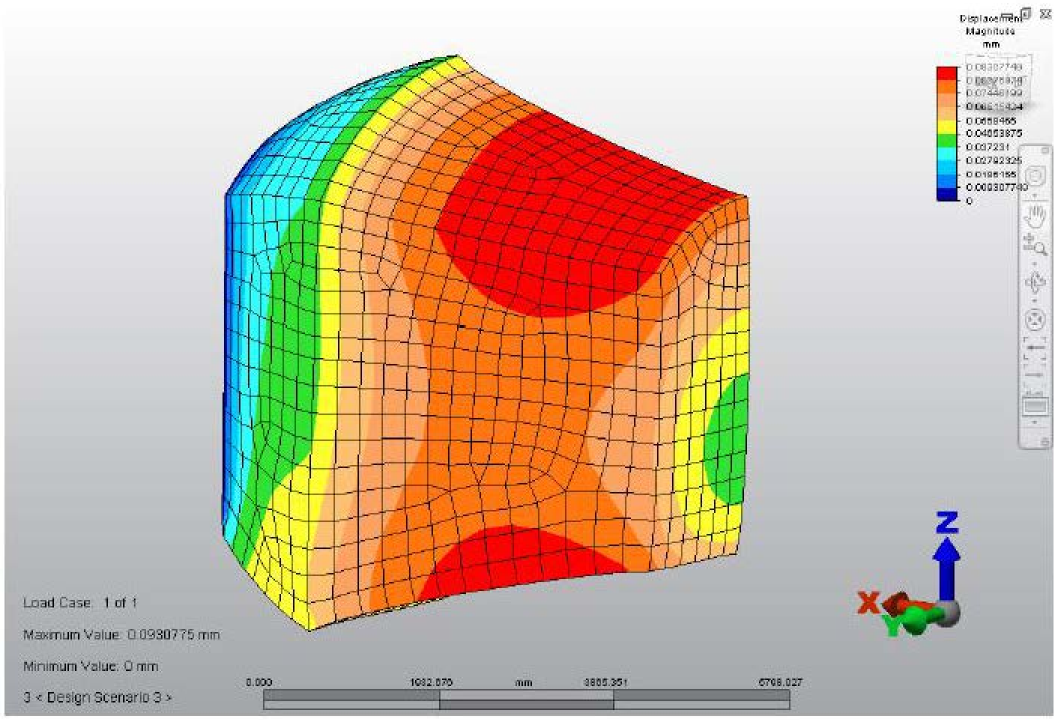

Fig. 6. Example of POPLU mechanical model, showing expected displacements.

The construction material developments within both POPLU and DOMPLU have included advances in cement-based and bentonite-based components used for plugs and seals. Comprehensive laboratory programs have been completed, in order to ensure use of the correct specifications in full-scale experiments and future operational conditions.

Low-pH cementitious materials have been developed in several projects for more than a decade, but still their use at full-scale requires modifications in mixes and laboratory verification of their properties before field use at a decametric scale.

The low-pH concrete recipes and requirements used in Sweden and Finland have been slightly different. The DOMPLU recipe is a self-compacting concrete with a lower maximum aggregate size of 8 mm and a water-to-binder ratio of 0.825. The mixture is composed of cement and silica fume and is designed to have little or no shrinkage. The full details about the DOMPLU recipe B200 and the resulting performance tests are described by Vogt et al. [8, 9]

This Swedish recipe was also considered the initial reference design for Posiva [2] but Posiva has also considered experience from Canadian low-pH concrete used in tunnel and shaft sealing experiments [10]. Within the scope of POPLU, the recipe has now been developed further to account for local materials and higher durability requirements.

The concrete recipe developed for POPLU is also highly workable with potentially slight vibration needed within the mould at the time of placement. The maximum aggregate size is 32 mm, includes granite rather than limestone filler and has a lower water-to-binder ratio ranging from 0.48 to 0.68. The recipe can either be of binary nature, using cement and silica fume as in Sweden, or may also be a ternary blend to replace part of the binder with high quality Danish fly ash. The chemical admixture used as the superplasticizer had to be replaced from a polycarboxylate-based superplasticizer (Glenium51 product) to a naphthalene-based chemical due to the foreign material acceptance criteria that are stricter when working in an actual repository setting such as ONKALO, where the use of organics is prohibited.

Laboratory analyses have been done for both binary and ternary blends recipes to check early age properties of workability, heat of hydration and setting time, as well as checking long term properties. These later-age assessments have focused on evaluating the mechanical and chemical evolution of the materials' performance, such as pH leachate levels, drying and autogenous shrinkage and cracking potential, chloride resistance, sulphate resistance, strength development, watertightness and erosion resistance. An example of the low-pH concrete performance characterizations are given in Table I, including the two alternative recipes (for POPLU.

In addition to the concrete recipe, low-pH grout recipes are also used for sealing the plug to tunnel rock gap in POPLU. These recipes and their performance are described, for instance in [11,12].

TABLE I. Examples of low-pH concrete performance results, compared to traditional high performance concrete and the target values for POPLU.

	POPLU Target	**POPLU Binary**	**POPLU Ternary**	**DOMPLU "B200"** [a]	**"Normal concrete"**
Compressive strength, MPa	> 50	91.5	79.5	67.5	50
Split tensile strength, MPa	3.2	5.6	4.5	-	3.2
Modulus of elasticity, GPa	34	37.4	34.2	-	34
Autogenous shrinkage, mm/m	(min)	0.22	0.15	0.03	0.1
Drying shrinkage, mm/m	(min)	0.17	0.22	-	0.6
Water tightness, mm	max 50	4.0	5.0	5.3	25
Chloride diffusivity, m^2/s	(min)	$2.1*10^{-12}$	$2.8*10^{-12}$		$10-20*10^{-12}$
pH of leachate at 90 days (reference/Groundwater)	< 11	11.4 / 10.3	11.4 / 10.3	11.4 / 10.3	>12,5

[a] *Results are based on re-production of mix in Finland*

The production of the bentonite components like pellets, backfill blocks, and seal layer blocks for the large-scale tests has demanded understanding of manufacturing and emplacement processes, including quality assurance, storage and transport of the materials, ensuring achievement of planned design and accounting for the interactions between cementitious- and bentonite-based components in field conditions. These bentonite components have been manufactured following the existing backfill reference designs in both Sweden and Finland, as given in Table II. The DOMPLU experiment has used the backfill materials, though the POPLU experiment uses only the concrete without backfill and sealing layers.

TABLE II. Backfill component, full-scale test design parameters.

	DOMPLU, Sweden	**POPLU, Finland**
Backfill & seal block dimensions	500 x 571 x 300 mm (180 kg)	550 x 470 x 330 mm
Backfill material & dry density	Asha, small bricks	Friedland clay, 1990-2070 kg/m^3
Seal layer, block material & density	MX-80 (w 17%), compaction by 20 MPa to 1680 kg/m^3	MX-80 (17% w), >1400 kg/m^3
Pellet fill material & dry density	MX-80, >900 kg/m^3	MX-80, 900-1100 kg/m^3

Instrumentation for Monitoring the Performance

Instrumentation and monitoring of full-scale experiments is required to gain information on plug feasibility, but also for assessment of the plug and seal behavior during accelerated testing conditions. Great emphasis was put on planning the monitoring needs and techniques, to ensure optimal use of results for performance and safety assessments. Full-scale tests offer a possibility to develop and test the monitoring of Engineered Barrier Systems, which is required by the regulatory guides in some of the DOPAS project's partner organizations.

DOMPLU was constructed with 45 sensors in the backfill and seal layer and another 56 sensors within the concrete. These were placed on-site at the same time as the backfill blocks. The sensors in the backfill and seal layer are lead through pipes in the rock to the neighboring tunnel, a distance of about 21 meters. Sensors within the concrete are lead out the front face of the concrete plug. The properties being measured by the array of sensors includes temperature, relative humidity, strain, displacement, pore pressure and total pressure.

The POPLU experiment has also been designed to include about 65 sensors in the concrete (Figure 7) and an additional 10 in the filter layer. Possible disturbances by monitoring are mitigated by using new techniques as much as possible, such as wireless sensors in parallel to traditional wired sensors, so that the full-scale experiments give the basis for future needs within plug and seal technologies for nuclear waste management. The instrumentation of POPLU is described in a separate paper in this same conference [13].

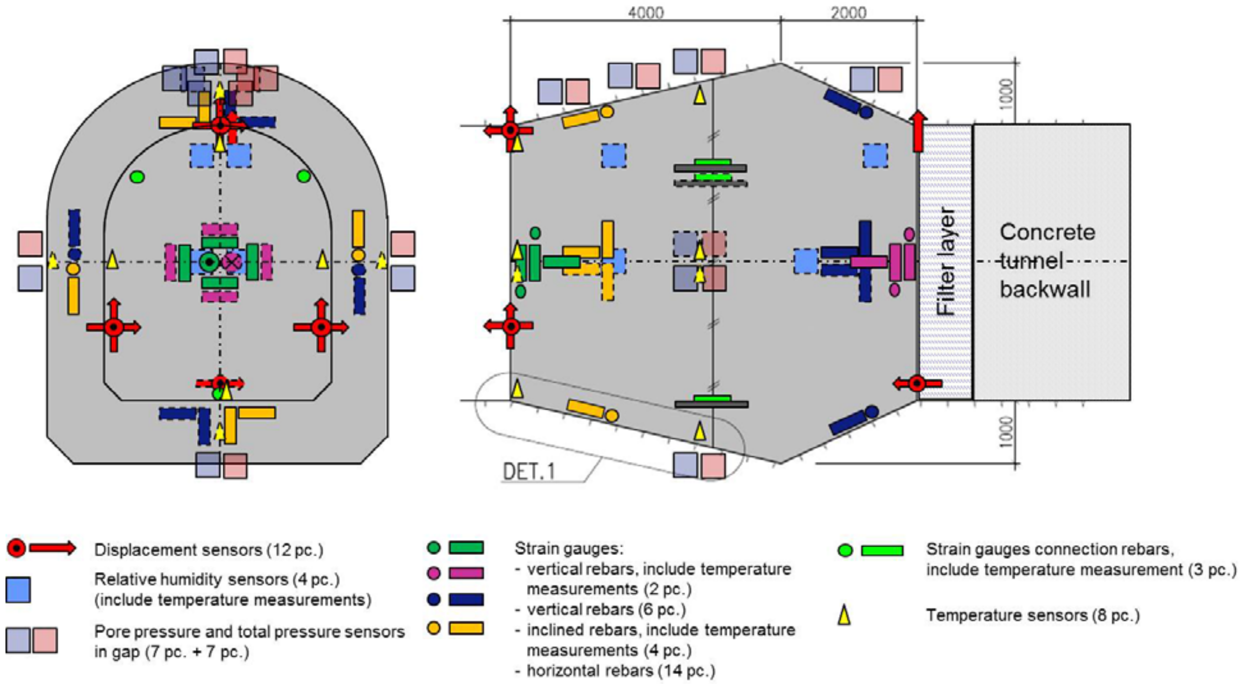

Fig. 7. Example of POPLU sensor locations for concrete instrumentation

Monitoring the Performance

Great emphasis is put on planning the monitoring needs and techniques during the accelerated loading of the plugs, to ensure optimal use of results for performance and safety assessments that can be collected, analyzed and used to forecast lifetime engineering. Part of the experimental planning is evaluating alternatives and verifying performance of alternative materials and their combinations to be used in the plug components.

DOMPLU and POPLU experiments have many common aspects despite their different structural and materials designs. Both of these Nordic plug experiments are located in crystalline rock type geological conditions and the plugs' functionality requirements are nearly identical. The plugs will have similar accelerated performance test durations and levels for evaluating the watertightness and mechanical integrity of the two alternative designs.

With the principal goal of monitoring water leakage though the plugs over time, a water collection system is installed downstream from each plug. The plugs are sheltered by a plastic sheet to create a tight atmosphere around the plug. Leakage water is collected by gravity to a suspended scale for on-line registration of the water-flow. The accelerated testing is achieved by using artificial pressurization with water behind the plug, and having incremental increases in pressurizing in steps over a one year period. The pressure is raised incrementally to 7 MPa for the actual tightness test and up to 10 MPa for a verifying strength test.

The monitoring of the DOMPLU experiment started in September 2013 (month 0) when the bentonite seal had been artificially wetted by flooding of the filter during the summer. When the drainage valves to the filter were closed, pressurization of the experiment started by the natural groundwater inflow, corresponding to about 100 kPa per week (month 1-2). From month 3, the pressurization system is operational, pumping in water for a faster pressure increase (about 250 kPa per week). At the end of month 3, the hydrostatic pressure had reached 1,1 MPa and the measured leakage rate past the plug was very low: 0.2 liters/hour. The leakage rate has been stable during the pressure increase, indicating a watertight function of the plug at prevailing pressure. The sensors are performing well (>95% are operational) and the monitoring is showing the expected trends. The swelling pressure of the bentonite seal is increasing slowly as expected. At the end of month 3 the measured swelling pressures in the bentonite seal were between 75-400 kPa. A fully watertight function of the seal is expected at about 500 kPa of swelling pressure. The total pressure is to be increased stepwise until 7 MPa is reached, holding this dimensioning pressure for some months. It is expected that the POPLU monitoring program will run from June 2014 through 2016.

The results of the monitoring program are used to evaluate the performance and compliance of the plugs to the requirements and safety functions of the plugs. At the conclusion of the pressurization test approximately two years after construction, monitoring data will be compared with the initial modeling forecasts. The structural and material reference designs as well as plug requirements may then be updated based on the experimental results obtained in both POPLU and DOMPLU. Sensitivity analysis is carried out, uncertainties and risks are also evaluated over the course of the project and the will be based on monitoring and model verification. These actions through these demonstrations allow for a higher level of confidence in the stakeholders by ensuring that future operation of repositories will meet the design and expectations on safety. In the future, the level of in-situ monitoring can be reduced based on the increased confidence gained by these early demonstrations.

CONCLUSIONS

The DOPAS -project has been running for nearly half of its four year duration and already major progress has been made. The achievements include for the concepts for deposition tunnel end plugs in Finland and Sweden that they have been designed and modeled based on the expected performance of over a 100 year plug lifetime. The two experiments of POPLU and DOMPLU are in similar types of geological environments, i.e. crystalline rock supporting the KBS-3V deposition concept. The plugs have been designed with similar performance requirements and thus will have similar accelerated loading and monitoring activities so that their performance can be compared.

New low-pH concrete materials have been developed and demonstrated for workability and durability properties. Elaborate monitoring systems have been designed and over 100 sensors have been installed in Äspö HRL at Sweden's on-going dome-plug experiment, which was built in early 2013. The POPLU wedge plug experiment in ONKALO; Finland is schedule to be in place in early 2014 in a drier environment compared with Äspö HRL and instrumented with about 80 sensors. The monitoring systems focus on the leakage and displacements within the plug, but are also used to track the evolution of the plugs and backfill evolution over time as a result of accelerated performance simulation, which is achieved through pressurization in steps. The expected mechanical and hydraulic performances of the plugs have been modeled during the design stage and the experimental results will be used to update the models, requirements and the designs.

All these actions carried out in the experiments of the DOPAS project support long-term safety demands and improving stakeholder confidence in repository operation. The plug performance experiences are collected and compared jointly between the two countries, and will be reported in 2015-16 within the DOPAS project.

The project outcomes can be used by the international waste management community to enhance the safety and especially location selection, design, construction and quality management practices for future tunnel plugs and seals used in various types of repository configurations and geological conditions.

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