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EURATOM

1. DOPAS 2016 FOREWORD

The four year's of research, development and demonstrationr work within DOPAS (Full scale demon stration of Plugs and Seals) Project was summarised in the international DOPAS 2016 Seminar held on May 2016 25th-27th in Turku and Olkiluoto, Finland.

About DOPAS Project

The Full-Scale Demonstration of Plugs and Seals (DOPAS) Project work was jointly funded by the Euratom Seventh Framework Programme of the European Commission (EC) and by European nuclear waste management organisations (WMOs). The DOPAS Project was undertaken during the period from September 2012 to August 2016. Fourteen European WMOs, research and consultancy organisations from eight European countries participated in the DOPAS Project. The Project was coordinated by Posiva Oy (Finland). A set of five full-scale experiments, materials research projects, and performance assessment studies on plugs and seals for geological repositories were undertaken in the course of the Project.

The DOPAS Project was initiated by the Implementing Geological Disposal of Radioactive Waste Technology Platform's (IGD-TP's) Executive Group as part of the deployment of the IGD-TP's Strategic Research Agenda.[1] Plugs and sealing structures are part of the operating modes of the disposal operations or of their closure. The development work is an important part of in industrialising these components of the repository on the way to achieving the IGD-TP vision ("Vision 2025") that *"by 2025, the first geological disposal facilities for spent fuel, high-level waste (HLW) and other long-lived radioactive waste will be operating safely in Europe" (IGD-TP*, 2009).

The RD&D work done is also needed to support the future disposal activities beyond 2025 and so the aim of the DOPAS project was to produce a roadmap and describe the procedures that could be beneficial for those organisations that are in the starting phase in their disposal programme development. However, the work contained in DOPAS is not limited to desk studies but rather involves practical learning using for example, full-scale demonstrations and related work phases and their iteration. This knowledge can be adopted for different development phases (conceptual design, basic design and detailed design) of repositories.

Main Purpose of Plugs and Seals

A variety of plugs and seal structures in different stages of operation and closure of premises is required for the future repositories in different host rock environments. In a generic sense, however, deposition tunnel plugs are needed as part of the operational phase in most geological media as their main functions are to prevent extrusion of the swelling backfill out from the deposition tunnel and prevent the possible formation of piping and erosion channels in the backfill resulting from groundwater inflows during the early stages of repository evolution. Later, either during the operational phase or in connection with the required drift closure, seals or plugs will be needed to isolate the disposal areas from the underground space and tunnels that are temporarily open during the disposal operations. Their mechanical and hydraulic properties are planned to limit the hydraulic flow or to support the maintenance of water

[1] IGD-TP (2011). Strategic Research Agenda. http://www.igdtp.eu/

tightness of the excavated underground openings. During the final closure of access routes and shafts into the disposal facility, plugs are also needed to keep the hydrogeological conditions stable. In addition, plugs are needed to seal the investigation holes that are not kept open for monitoring purposes in the vicinity of the repository.

In practice the plugs have different functions at different periods of their lifetime, and that makes the design of the structures challenging. During the whole assessment period of the repository, all plugs need to be chemically stable and fit together with the host rock where they will be emplaced. The (deposition tunnel) plugs that were further developed within DOPAS Project are first needed for industrial production in the mid-2020s in Posiva's disposal facility and at different times after this for repositories planned by other countries. The DOPAS Project has provided lessons learned and practical aspects for their production and these experiences can be utilised for different repository components.

The full-scale Demonstrations Of Plugs And Seals with related research and development activities culminated in a three-day seminar DOPAS 2016. The first two days (Wednesday and Thursday) were held in Turku on 25 and 26.5.2016 and the third day (Friday, 27.5.2016) was held in Olkiluoto, both in west of Finland. The location of this seminar was selected due the fact that one of the DOPAS experiments was constructed at the nearby Olkiluoto site. The field trip on 27 May 2016 allowed for a site visit and an opportunity to hear more about the POPLU experiment and to see the crystalline host rock formation, where the first purpose-built spent fuel repository will be constructed. The DOPAS 2016 Seminar was originally planned to be held jointly with IGD-TP, but since the DOPAS 2016 was a topical seminar for plugs and seals it was arranged independently, but using IGD-TP as advertisement route to reach all the European WMO's and other participants in the IGD-TP.

What did the DOPAS 2016 seminar give to the audience?

The DOPAS 2016 seminar program was drawn up in such a way that that the lessons learned can be used not only in the development of plugs and seals structures, but also more widely in the demonstration of repository components and structures, and even in other industries.

Still the main target of the seminar was to present the main outcomes from DOPAS Project and this was done in phases. The DOPAS 2016 Seminar was structured to present summary conclusions from the DOPAS Project at the start of the Seminar. In this way, the audience was introduced to key conclusions at the start, which allowed the context of more detailed information to be understood ahead of time. The seminar also benefitted from Panel Sessions in which the experiment leaders were able to provide the benefit of their experience direct to the seminar participants. And, in particular they were able to address audience questions that were submitted to an electronic bulletin board via the internet during the meeting. The Seminar Programme Committee also invited specific presentations from outside of the DOPAS Project to bring in the experiences in the design of plugs and seals f from the other industries e.g. oil and gas, mining, and carbon sequestration.

The seminar allowed people to meet and to exchange knowledge and experiences about the plugs and seals or demonstration related work. The background of the audience was from various waste management organisations to consultants and other organisations, which have commenced or will initiate such demonstrations. Specifically, the 110 participants included representatives from waste management organisations, from technical support organisation's

(TSOs) working with development issues, from universities with both professors and researchers and post-graduate students, design engineers and materials developers, companies producing cementitious and bentonite materials, and safety authorities. Over 50 organisations from sixteen countries, mostly from Europe, participated to the DOPAS 2016 seminar. The programme was well-balanced and the participant expectations were well fulfilled as confirmed by their feedback given for seminar planning team.

DOPAS 2016 Seminar Structure

The DOPAS 2016 Seminar programme was organized as follows:

- During the opening session, the general level background into the demonstrations and status of European research programme was provided as basic introductions to the DOPAS Project. This included presentation of the main achievements and lessons learned by the DOPAS Coordinator, Experiment leaders and Work Package leaders for related demonstration (DEM) and research and technology development (RTD) work. The first afternoon was used for gathering information from the experiences or experiments on plugs and seal developed and implemented for other the geological disposal uses including their state of the art in development areas related to the plugs and seals.
- The second day was initiated by more detailed information on plug and seal design, on host rock and material issues, and on the long-term safety related aspects and how the plugs and seal are treated in the safety case. At the end of the second day, the DOPAS Training Workshop was presented and the Finnish nuclear safety authority highlighted the experiences from supervising the spent fuel disposal programme of Posiva and follow-up procedures of the POPLU experiment. The second day was ended with a panel discussion, where the experiment leaders could answer the questions posted by seminar audience during the two seminar days.
- The third day involved an Olkiluoto site visit for the two busloads of preregistered seminar participants. This visit provided an opportunity to hear more details about one of the DOPAS experiments, POPLU plug. POPLU involved construction and testing of a concrete plug in a demonstration area in the underground rock characterisation facility ONKALO that will be integrated into the underground disposal facility for spent nuclear fuel in, located at Eurajoki, Finland, that has been awarded a construction license in November 2015.

DOPAS 2016 Seminar planning team wishes to thank the European Commission, the waste management organisations, and the independent seminar rapporteur Professor Emeritus Pierre Berest from Ecole Polytechnique, Palaiseau, France. Further thanks goes to all DOPAS 2016 Seminar participants.

2. DOPAS 2016 PROGRAMME

DAY ONE, Wednesday 25 May 2016, Turku Radisson Blu

Session 1: Opening ceremony and keynote presentations highlighting European cooperation in demonstrating repository feasibility Chair: Johanna Hansen Co-chair: Matt White		
Time	Title	Authors
0900-0910	Opening of the DOPAS 2016 Seminar	Johanna Hansen, DOPAS coordinator *Posiva Oy, Finland*
0910-0920	Welcome from Posiva	Erkki Palonen, Corporate Adviser *Posiva Oy, Finland*
0920-0940	Programme status in radioactive waste management and strategic evolution in support to R&D	Christophe Davies, Project Officer *European Commission, Belgium*
0940-1010	Role of demonstrations for a spent fuel repository concept	Monica Hammarström, Director, International Relations *Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden*
1010-1040	Overview of the DOPAS Project	Johanna Hansen, DOPAS Coordinator *Posiva Oy, Finland*
1040-1105	**BREAK**	

Session 2: Key conclusions from the DOPAS Project (Part 1) Chair: Marjatta Palmu Co-chair: Jan-Marie Potier		
Time	Title	Authors
1105-1110	Introduction	
1110-1130	Objectives and main outcomes from the DOPAS full-scale demonstrators: FSS, EPSP, DOMPLU, POPLU and ELSA	DOPAS Experiment leaders in Panel Régis Foin[1], Jiri Svoboda[2], Pär Grahm[3], Petri Koho[4] and Michael Jobmann[5] *[1]Andra,France,* *[2]Czech Technical University, Czech Republic* *[3]Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden* *[4]Posiva Oy, Finland* *[5]DBE TECHNOLOGY GmbH (DBE TEC), Germany*
1130-1200	Design basis of plugs and seals	Matt White[1], Behnaz Aghili[2] and Slimane Doudou[1] *[1]Galson Sciences Limited, United Kingdom* *[2]Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden*
1200-1230	Progress on the design and implementation of plugs and seals in the DOPAS Project	Jean-Michel Bosgiraud[1], Matt White[2] and Slimane Doudou[2] *[1]Andra, France* *[2]Galson Sciences Limited, United Kingdom*
1230-1400	**LUNCH AND POSTER SESSION**	

Session 2: Key conclusions from the DOPAS Project (Part 2) Chair: Jan-Marie Potier Co-chair: Marjatta Palmu		
Time	Title	Authors
1400-1425	Performance assessment of plugs and seals	André Rübel, *Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Germany*
1425-1450	Application of lessons learned during the DOPAS Project to less advanced waste management programmes – Case study: Radioactive Waste Management Ltd	Dean Gentles[1], Wolfgang Kickmaier[2], Matt White[3], Slimane Doudou[3] and Alastair Clark[2] [1]*Radioactive Waste Management Limited, United Kingdom* [2]*McCombie, Chapman, McKinley Consulting, Switzerland* [3]*Galson Sciences Limited, United Kingdom*
1450-1515	**BREAK**	
Session 3: Plugging and sealing experiences from other applications **Chair: Dean Gentles** **Co-chair: Jiri Svoboda**		
Time	Title	Authors
1515-1520	Introduction	
1520-1540	Treatment of seals and sealing systems in total system performance assessment	Mark Crawford[1], Dan Galson[1] and Lucy Bailey[2] [1]*Galson Sciences Limited, United Kingdom* [2]*Radioactive Waste Management Limited, United Kingdom*
1540-1600	Full-Scale tunnel and shaft seals: Tunnel Sealing Experiment (TSX) and Enhanced Sealing Project (ESP) at the Underground Research Laboratory (URL) in Canada	D.A.Dixon[1], D.Priyanto[2], J.B.Martino[2], P.Korkeakoski[3], R.Farhoud[4] and K.Birch[5] [1]*Golder Associates Ltd., Canada;* [2]*Canadian Nuclear Laboratories, Canada;* [3]*Posiva Oy, Finland;* [4]*Andra, France;* [5]*Nuclear Waste Management Organization (NWMO), Canada,*
1600-1620	The Gas-Permeable Seal Test in the Grimsel Test Site	Thomas Spillmann[1], B. Lanyon[2], R. Senger[3], Paul Marschall[1] and Jörg Rüedi[4] [1]*Nagra, Switzerland* [2]*Fracture Systems, United Kingdom* [3]*Intera, USA* [4]*Pöyry, Switzerland*
1620-1640	Experiences from an *in situ* test site for a sealing element in shafts and vertical excavations in rock salt	Beatrix Stielow[1], Jürgen Wollrath[1], Matthias Ranft[1], Monika Kreienmeyer[2], Thomas Schröpfer[2] and Jan Bauer[2] [1]*Bundesamt für Strahlenschutz (BfS), Germany* [2]*Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE), Germany*

1640-1700	Development of a UK approach to sealing deep site investigation boreholes: knowledge transfer from other industries	Francois Groff[1], Nick Jefferies[2] and Simon Norris[3], [1]*Schlumberger, United Kingdom* [2]*Amec Foster Wheeler, United Kingdom* [3]*Radioactive Waste Management Limited, United Kingdom,*
1700-1715	Posiva plans and experiences for borehole closure	Taina Karvonen[1] and Johanna Hansen[2] [1]*Saanio & Riekkola Oy, Finland* [2]*Posiva Oy, Finland*
1715-1730	Conceptual sealing strategy and initial performance assessment for the Chandler Storage and Isolation Facility	Steve Reece *Tellus Holdings, Australia*

DAY TWO Thursday 26 May 2016, Turku Radisson Blu

Session 4: Design, siting and construction of plugs and seals (Part 1) **Chair: Jean-Michel Bosgiraud** **Co-chair: Behnaz Aghili**		
Time	Title	Authors
0810-0815	Introduction	
0815-0835	Initial plug and seal design for the Dutch repository concept	Philip J. Vardon[1], Jiao Yuan[1], Michael A. Hicks[1], Yajun Li[1] [1]*Geo-Engineering Section, Delft University of Technology, the Netherlands*
0835-0855	Development and performance of various low-pH cementitious materials for plugs and seals in geological disposal demonstrations (DOPAS Project)	Erika Holt[1], Markku Leivo[1], Tapio Vehmas[1], Jari Dunder[2], Elina Paukku[3], Behnaz Aghili[4], Jiří Svoboda[5], Petr Večerník[6], Xavier Bourbon[7], Sandrine Bethmont[7], Jean-Michel Bosgiraud[7] and Matt White[8] [1]*VTT Technical Research Centre of Finland Oy, Finland* [2]*Posiva Oy, Finland* [3]*Sweco Rakennetekniikka Oy, Finland* [4]*Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden* [5]*Czech Technical University, Czech Republic* [6]*ÚJV Řež a.s, Czech Republic* [7]*Andra, France* [8]*Galson Sciences Limited, United Kingdom*
0855-0915	FSS (Full-Scale Seal) Experiment transposition from laboratory tests to full-scale emplacement reality (DOPAS Project)	Regis Foin and Jean-Michel, Bosgiraud *ANDRA, France*
0915-0930	Preparations before experiments - production for plug locations for DOMPLU and POPLU (DOPAS Project)	Sanna Mustonen[1] and Pär Grahm[2] [1]*Posiva Oy, Finland* [2]*Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden*
0930-1000	**BREAK**	

Session 4: Design, siting and construction of plugs and seals (Part 2) Chair: Jean-Michel Bosgiraud Co-chair: Behnaz Aghili		
Time	Title	Authors
1000-1020	DOMPLU plug filter and seal design, construction and results (DOPAS Project)	Pär Grahm[1] and Mattias Åkesson[2] *[1]Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden* *[2]Clay Technology AB, Sweden*
1020-1035	Bentonite based materials for the Full-Scale Emplacement (FE) experiment: design and production steps	Benoit Garitte[1], Herwig R. Müller[1], Hanspeter Weber[1], Frank Ooms[2], Martin Holl[3] and Sébastien Paysan[4] *[1]National Cooperative for the Disposal of Radioactive Waste (Nagra), Switzerland* *[2]CEBO, The Netherlands* *[3]JRS, Germany* *[4]Laviosa MPC, France*
1035-1050	Horizontal bentonite backfilling and concrete plug for the Full-Scale Emplacement (FE) experiment at the Mont Terri URL: requirements, design, instrumentation and emplacement	Benoit Garitte[1],Sven Köhler[1], Herwig R. Müller[1], Toshihiro Sakaki[1], Tobias Vogt[1], Hanspeter Weber[1],Martin Holl[2], Michael Plötze[3], Volker Wetzig[4], Moreno Tschudi[5], Heinz Jenni[6], Tim Vietor[1] Eric Carrera[7], Gerd Wieland[7], Sven Teodori[8], José-Luis García-Siñeriz Martínez[9] and Frank Jacobs[10] *[1]National Cooperative for the Disposal of Radioactive Waste (Nagra), Switzerland* *[2]J.Rettenmaier & Söhne, Germany* *[3]ETH, Switzerland* *[4]VersuchsStollen Hagerbach, Switzerland* *[5]Belloli, Switzerland* *[6]Rowa, Switzerland* *[7]Amberg Engineering, Switzerland* *[8]ÅF-Consult, Switzerland* *[9]AITEMIN, Spain* *[10]TFB, Switzerland*
1050-1110	Hydro-mechanical and chemical-hydraulic behaviour of different types of shaft sealing materials (DOPAS Project)	Oliver Czaikowski, Kyra Jantschik, Helge C. Moog, Klaus Wieczorek and Chun-Liang Zhang *Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Braunschweig, Germany*
1110-1130	Performance of Czech Bentonite Material in the Plug in Geological Disposal Demonstrations.	Večerník Petr[1], Vašíček Radek[2], Šťástka Jiří[2],Trpkošová Dagmar[1], Havlová Václava[1], Hausmannová Lucie[2], Smutek Jan[2], Svoboda Jiří[2] and Dvořáková Markéta[3] *[1]ÚJV Řež,; Czech Republic* *[2]Czech Technical University, Czech Republic* *[3]SURAO, Czech Republic*
1130-1255	**LUNCH AND POSTER SESSION**	

Session 5: Performance of plugs and seals
Chair: André Rübel
Co-chair: Pär Grahm

Time	Title	Authors
1255-1300	Introduction	
1300-1320	Instrumentation and monitoring systems for evaluation of plug responses in geological disposal demonstrations (DOPAS Project)	Erika Holt[1], Edgar Bohner[1], Torbjörn Sandén[2], Richard Malm[3], Jaroslav Pacovsky[4], Jiri Svoboda[4] and Matt White[5] *[1]VTT Technical Research Centre of Finland Oy, Finland* *[2]Clay Technology AB, Sweden* *[3]Sweco AB, Sweden* *[4]Czech Technical University, Czech Republic* *[5]Galson Sciences Limited, United Kingdom*
1320-1340	REM (Resaturation test at metric scale): Preliminary hydraulic simulation (DOPAS Project)	Antoine Pasteau[1], Jacques Wendling[1], Nathalie Conil[1] and Claude Gatabin[2] *[1]Andra DRD/EAP, France* *[2]CEA/LECBA, France*
1340-1400	Integration Of demonstrator activities in performance assessment: analysis of processes and indicators (DOPAS Project)	Jaap Hart, Ecaterina Rosca-Bocancea, Thomas Schröder and Jacques Grupa *Nuclear Research and Consultancy Group (NRG), The Netherlands*
1400-1420	Quantitative versus qualitative performance assessment of closure	Heini Reijonen[1], Pirjo Hellä[1], Nuria Marcos[1], Barbara Pastina[2] *[1]Saanio and Riekkola Oy, Finland* *[2]Posiva Oy, Finland*
1420-1440	Towards robust models of well seals and plugs in CO_2 storage sites	Richard Metcalfe, James Wilson and Steven Benbow *Quintessa Limited, United Kingdom*
1440-1510	**BREAK**	

Session 6: Concluding remarks: current status of repository plugging and sealing
Chair: Erika Holt
Co-chair: Frédéric Bernier

Time	Title	Authors
1510-1530	DOPAS Training Workshop 2015	Marjatta Palmu[1] and Radek Vašíček[2] *[1]Posiva Oy, Finland* *[2]CTU, Czech Republic*
1530-1550	Regulatory point of view on the demonstration of the feasibility of plugs and seals for the final	Pekka Välikangas *Radiation and Nuclear Safety Authority (STUK), Finland*

	repository of radioactive nuclear waste	
1550-1630	Current status of repository plugging and sealing and remaining technical and operational issues (DOPAS Experiments)	Panel session facilitated by Erika Holt[1], with an introduction by Matt White[2], followed by DOPAS Experiment leaders: Régis Foin[3], Jiri Svoboda[4], Pär Grahm[5], Petri Koho[6] *[1]VTT Technical Research Centre of Finland Oy, Finland* *[2]Galson Sciences Limited, United Kingdom* *[3]Andra,France,* *[4]Czech Technical University, Czech Republic* *[5]Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden* *[6]Posiva Oy, Finland*
1630-1650	Rapporteur's summary	Pierre Berest *Ecole Polytechnique, Palaiseau,, France*
1650-1700	Closing remarks	Johanna Hansen *Posiva Oy, Finland*

3. DOPAS 2016 RAPPORTEUR'S SUMMARY

RAPPORTEUR COMMENTS: IMPRESSIONS FROM THE DOPAS 2016 MEETING

Pierre Bérest, Ecole Polytechnique, Palaiseau, France

Containment of radionuclides is provided by several complementary barriers, waste forms, engineered barriers (canister, buffer, backfill, seals) and the geological formation. The DOPAS 2016 Seminar arranged in Turku, Finland, was a topical seminar dedicated to a presentation of the results of a 48-months effort in the frame of DOPAS (Full-Scale Demonstrations of Plugs and Seals), a project supported by the European Union's Seventh Framework Programme (Euratom), which addresses demonstration of engineered barriers (and especially seals and plugs).

The scientific rapporteur, who did not take part in the project, was asked to summarize the DOPAS 2016 Seminar. Remarkable syntheses of the seven work packages were presented during the six Sessions of the meeting (White et al. (a,b), Palmu and Vašíček). In this brief summary, the objective of the rapporteur is to choose several topics addressed during the meeting and to provide a transversal view of these topics.

A great asset of this meeting was that extended abstracts and presentations were not restricted to the DOPAS Project alone, allowing comparison with experiments performed in different frameworks and providing a broader perspective and a clearer picture of the state of the art. Therefore, in this summary, a distinction is made between DOPAS-related experiments and other experiments belonging to the same scientific field. All references mentioned in this summary are available at DOPAS 2016 web site:
http://www.posiva.fi/en/dopas/dopas_2016_seminar

"*Plugs and seals are composite structures, with specific components required to deliver the safety functions.*" (DOPAS, Gentles et al.) A seal basically comprises five elements: the host rock (rock salt, indurated clay, plastic clay and crystalline), the plugs (or abutments), the bentonite seal and the various interfaces between these three first elements, interfaces of which the Excavated Damaged Zone (EDZ) and the contact surfaces are the most important.

Contributions to the study of these elements are presented first, followed by some general comments.

Note that in this summary, the word *swelling clay*, which usually is montmorillonite-rich bentonite (bentonite), denotes materials used as part of the plug composite structure or other engineered barrier system (EBS) components like backfill or buffer. The bentonite material can be used alone, in several forms and densities (powder, pellets, blocks), or mixed together with other materials (crushed rock, sand, cementitious materials etc.), depending on the specific design of plugs or seals.

HOST ROCK

The host rock itself was not a topic studied in the DOPAS project, but host rock have constraints and conditions for implementing plugs and seals structures. The plug locations needs to be carefully selected and the requirements and procedure for selection of host rock was one of the key issues and were presented during the DOPAS 2016 site visit. However**,** Mikake et al. described experiments performed in the Mizunami Underground Research Laboratory (URL) in Japan; they proved that groundwater inflow in a crystalline host rock can be reduced significantly by optimizing the pre- and post-excavation grouting.

PLUGS

Plugs (also called « abutments ») must fill several functions: first, they must withstand swelling pressure from other parts of the engineered barriers (e.g., buffer or backfill consisting of bentonite) and from possible swelling clay element in the plug structure; but also, to a certain extent, prevent fluid outflow and bentonite erosion. A low initial permeability to air (and water) might be required before bentonite swelling is completed. To ensure initial tightness, the rock/concrete interface is grouted, and bentonite tapes (to support the tight contact between rock/concrete) are installed. In the long term the cementitious material used in the plug has no tightness requirement but it contributes to voids filling. The ability for cementitious plugs alone to hinder fluid flow was studied in the POPLU Experiment. Low hydration heat (to minimize cracking during cooling) and a low-pH plume, in the order of 11 or less, are needed to maintain the desired properties of the plug, i.e., to keep the plug materials water tight and to limit chemical interactions with other components. A remarkable synthesis of the lessons learned from the DOPAS full-scale demonstrations, Experiment 1 FSS (France), 2 EPSP (the Czech Republic), 3 DOMPLU (Sweden), 4 POPLU (Finland), regarding material development and monitoring and implementation were presented in DOPAS, Holt et al., (b) and (a), respectively. Other aspects presented during the seminar are described in more detail in the DOPAS Experiment summary reports (Foin & Bosgiraud et al., 2016, Svoboda et al., 2016, Grahm et al., 2015 and Holt & Koho, 2016).

The Full Scale Seal (FSS) experiment was built inside a drift model in a hangar at ground level (Foin and Bosgiraud). The objective was to test the clay core and containment walls in conditions close to scale 1 and to examine the scale aspects. A low-pH Self Compacting Concrete (SCC) and a low-pH shotcrete were tested. Before the test, many iterations allowed determination of the three best compositions, which were actually tested. For the low-pH SCC, the results were quite successful. For the low-pH shotcrete, the hydration temperature was too high (67 °C instead of less than 50 °C), and cracks in the downstream containment wall were observed.

The Experimental Pressure and Sealing Plug experiment (EPSP) investigates the various processes underway inside the components of a plug. The test, performed in the Josef URL in the Czech Republic, is generic, as the future host rock and disposal site are unidentified. The inner and outer concrete plugs used sprayed glass-fibre concrete with relatively low pH. The inner chamber can be filled with air, water or bentonite slurry. Emphasis is put on development of instrumentation and monitoring, and data acquisition (Svoboda et al.)

The dome plug test (DOMPLU) constructed at Äspö Hard Rock Laboratory, Sweden, consists of a bentonite seal whose displacements are restrained by an octagonal plug (diameter 8.8 m, thickness 1.79 m) cast in situ with low-pH concrete (DOPAS, Grahm and Åkeson). The design load is 7 MPa, and the water flux through the plug must be smaller than 0.1 l/min. Water pressure behind the plug was increased incrementally to 4 MPa. Several months later, the flow was 44 ml/min; one year later, it was divided by a factor of two. An alternative design, consisting of a wedge-shaped reinforced concrete structure, is tested in the POPLU project implemented in ONKALO underground rock characterisation facility (DOPAS, Mustonen and Grahm, reported in Holt and Koho). In POPLU, bentonite seal was excluded and it was possible to pressurise the concrete part only; the location of plug drilling, was changed; wedging and grinding (instead of wire sawing) was used. Factors influencing tightness were analysed, another type of production and different recipes and designs were tested.

Several other presentations summarized experiments, which had not been performed in the DOPAS framework. Vardon et al. suggest an initial design for the plugs that will seal off the drifts of a disposal in the Dutch repository in Boom clay. Two designs, with or without lining removal, are proposed. Emphasis is put on mechanical stability. The swelling pressure is transferred to the rock mass via friction (when the lining is removed) and via compression to the concrete lining beyond the plug (when the lining is not removed). Length of the seal is optimized to minimize water flow and pressure gradient.

The plug of the Full-Scale Emplacement (FE) test at the Mont Terri URL (Opalinus clay) was designed as a friction-controlled plug (Garitte et al. (b)) to withhold a potential swelling pressure of 3.5 MPa (dry density 1.45 t/m^3). However, oxygen sensors close to the retaining wall are sensitive to atmospheric pressure in the access tunnel, proving that it is difficult to achieve absolute tightness of a seal crossed by 750 instrumentation cables.

BENTONITE COMPOSITION

Plug tightness in most designs rely on a swelling material core, or a special swelling material seal behind the concrete plug, and sometimes in the backfill behind the concrete plug. In experiments and tests conducted as part of DOPAS, the objective was to study the whole plug structure, including all its components and, therefore, the behaviour of bentonite alone is not assessed.

For the DOPAS FSS experiment, a pure Wyoming sodium bentonite (Montmorillonite) was used, with the objective of reaching a dry density around 1.62 t/m^3 (hydration pressure of 7 MPa), Foin and Bosgiraud. During the REM experiment the same materials as in FSS with similar specifications, a mixture of pellets and crushed pellets of bentonite was used (Pasteau et al.) to study the hydration properties of the bentonite core.

For the DOPAS EPSP experiment, Večernik et al. characterized a Czech Ca-Mg bentonite: for 40-mm long and 12-mm diameter pellets, the maximum dry density was around 1.8 t/m^3.
The DOMPLU bentonite seal consists of a 0.5 m stack of highly compacted MX-80 bentonite blocks, with water content of 17 % with a resulting dry density of about 1.7 t /m^3, and a surrounding MX-80 pellet filling closest to the rock.

In the frame of the DOPAS THM-ton project, a part of the ELSA phase 2 supporting studies (Czaikowski et al.), crushed Callovo-Oxfordian (Cox) claystone produced by excavation is considered for backfilling the openings and, mixed with bentonite, for sealing boreholes, drifts and shafts. Compacted samples have a water permeability of 10^{-19} m^2 at a 30% porosity (gas permeability is higher). Various Cox claystone/MX80 bentonite ratios were tested. High swelling capacities and low permeability were observed.

Other projects in which bentonite seals have been studied were presented during the DOPAS seminar, providing an opportunity for information exchange between other ongoing projects and organisations working on similar issues. In the FE experiment, conducted as part of LUCOEX project, highly compacted bentonite granules were used; a minimum dry density of 1.45 t/m^3 was targeted; different assessment methods were run; and uncertainties were assessed. The overall as-measured density is 1.489 ± 0.006 t/m^3 (Garitte et al. (b)). A clear and simple recipe for a granular bentonite mixture at industrial scale was proposed. An average bentonite density of 1.78 kg/m^3 was achieved through adjustment of the initial water content and of the compaction pressure. For the possible German repository in clay formation (Jobmann and Herold), canisters are emplaced in short vertical boreholes equipped with a bentonite seal and concrete abutment. The seal is an in-situ compacted mixture of pellets (70-80% mass) and loose bentonite, which is expected to have dry bulk densities between 1.6 and 1.8 t/m^3. During the Gas-Permeable Seal Test in the Grimsel Site (GAST), an 8-m long, 3-m diameter seal composed of 20% bentonite - 80% quartz sand was used. The objective of this test was to prove that such a composition allows releasing gas generated in the repository, as such a mixture has a low gas-entry pressure, a low water permeability (10^{-18} m^2), and enhanced gas permeability. The target was 1.7 t/m^3; the obtained dry densities ranged between 1.6 and 1.73 t/m^3 (Spillmann et al.). When modelling reactive transport in bentonite shaft seals, Wilson et al. consider a 70/30 bentonite/sand mixture.

PLUG INTERFACES: THE EDZ AND CONTACT SURFACES

THE EDZ

The excavation damaged zone (EDZ) is an annular zone, at the wall of any deep gallery, in which micro-fractures develop and possible chemical changes take place. Rock permeability in the EDZ may increase accordingly; see for instance European Commission (2003). The EDZ is present in any host rock: crystalline rock, rock salt, indurated or plastic clay. It is an issue in safety assessment, as this rock sheath around a seal or a plug might be a short cut for nuclide transport or groundwater flow. However, one must not be interested in the EDZ as it is after excavation but, rather, as it will be in the long term. The seal must play its role effectively over several thousands of years (Rübel). Significant evolution of the EDZ is possible during this period.

The role of the EDZ is studied in organisations participating to the DOPAS and reported elsewhere. The DOPAS experiments have tested the practical methods to remove the EDZ using the slot excavation methods in crystalline rock (both DOMPLU and POPLU), and recesses in clay rocks (FSS). The EDZ will be removed in salt rock (Bollingerfehr et al. 2013) as well, but the corresponding methods were not tested in the DOPAS Project.

This topic was also addressed in presentations of other experiments (not belonging to the DOPAS programme). For example, Su et al. measured the post-failure behaviour and permeability increase of the Cobourg limestone, considered as a possible host rock in Canada. A preliminary evaluation of the possible EDZ thickness in such a rock formation is 1.1 m. Increased porosity in this zone was considered by Wilson et al. when modelling reactive transport model. Spillmann et al. suggest that in a tunnel in the Grimsel test site excavated by a tunnel boring machine from Opalinus clay at a 400-m depth, the hydraulic conductivity of the EDZ is "*in the same range or lower than that of the seal.*" Vardon et al. presented a conceptual design of a repository in Boom clay in which "*the bentonite seal may be able to reseal the EDZ via swelling behaviour.*" Jobmann and Herold discuss the example of German repository design in clay formations. The permeability of the sealing location includes the EDZ, the contact zone and the seal itself; only limited data are available when the EDZ is concerned.

INTERFACES

Večernik et al. described the Physical Interaction Model (PIM) between bentonite, concrete and water, as part of the DOPAS EPSP project. Synthetic granitic water was used as the liquid phase. Some interaction process occurs, but the rate was not significant and did not influence the material safety properties. Still the duration was too short to derive definite conclusions.

Several authors discussed the long-term evolution of the bentonite-rock interface in a seal, a possible weak point in the long term when alteration degrades the bentonite properties. Wilson et al. compute the behaviour of shafts sealed with a 70/30 bentonite/sand mixture in contact with a highly saline and Mg-rich thick shale formation above the Cobourg limestone formation. Timescales of up to 100 000 years were investigated. Dissolution/precipitation kinetics was fully coupled with the evolution of the porosity. Pore-water salinity is high, and the Pitzer approach was preferred to standard models. Over 100 000 years, alteration of the primary phases is restricted to a narrow band around the shaft seal-rock interface.

A different but related topic was discussed by Metcalfe et al., who computed the chemical behaviour of cement plugs in abandoned access boreholes of an underground CO_2 storage facility. Here, again, the Pitzer approach was selected, and the modelling results were compared to 30-year old samples cored from a cemented well. Cement's porosity is sealed with amorphous silica and calcite after about 100 years. The authors recognize that geochemical degradation is likely to be less significant than defects associated with cement emplacement.

PERMEABILITY OF BENTONITE

In principle, the flow through the bentonite seal can be described by Darcy's law, which describes a linear relation between the flow rate and the pressure gradient. Bentonite studies in DOPAS Experiments (and in other plug-and-seal related works) have contributed to a better understanding of bentonite behaviour. Several papers proved that advanced modelling might be necessary.

Czaikowski et al. proved that when a COX claystone powder + MX-80 bentonite mixture (60/40 or 40/60) is compacted, water permeability can be as low as $2\text{-}3 \cdot 10^{-20}$ m^2 (similar to intact Bure-clay permeability); compacted claystone (with no bentonite) also exhibits low permeability. The permeability to the gas in a coarse-grained ($d < 10$ mm) sample is larger than that of water. This result suggests that the poro-hydro-mechanical behaviour of a seal might be complex. Pasteau et al. discuss the preliminary results of a re-saturation test (REM) performed at a metric scale with a mixture of bentonite pellets and powder. They conclude that coupled hydro-mechanical modelling (and longer test duration) will be needed for more in-depth investigations: a double porosity model might be required. Trpkošova explained that, after 10 000 years (the minimum requirement for the lifetime of a container of spent fuel), the bentonite will be saturated and could be exposed to increased water flow and erosion, with significant consequences for the effective dose rate and the dominant radionuclides. Spillmann et al. discussed a Gas-Permeable Seal Test in which the sand/bentonite ratio, 80/20, is larger than usual, and the permeability to gas is significantly higher than the permeability to water. Such notions as generalized Darcy flow (to gas and water), and poro-mechanical coupling may prove to be needed.

EMPLACEMENT

Measuring permeability of a bentonite seal at full scale (with respect to time and space) is a difficult challenge. Within the DOPAS Project, several ways to meet this challenge are tested and presented. Some of the tests have been done at various scales; some of the tests have been modelled; in other tests, the objective was to reach the initial state, as required in the planned conditions; the expected results will be reached after a period of time longer than the duration of the DOPAS Project. In principle, permeability of saturated bentonite is related closely to its initial dry density. However, emplacement is an important factor for the initial dry density, and heterogeneity in dry density is difficult to avoid, especially in places where compaction is more difficult. In this context, quality assurance is a key item for emplacement and has been developed further within DOPAS.

The FSS experiment, a part of the DOPAS project, is an example of the challenges raised by upscaling. In this experiment, a drift model at ground level is used, with its diameter and length close to those of an actual drift (Foin and Bosgiraud). The objectives were an overall permeability (after saturation) of 10^{-18} m^2 and a swelling pressure of 4 MPa. A 1.62 t/m^3 dry density was achieved in the laboratory; however, at larger scale, this figure was revised downward, to 1.5 t/m^3. In the lower part of the mock drift, a 1.58 t/m^3 density was reached, but it was 1.29 t/m^3 at the top of the model.

The emplacement issue was also raised in other field experiments. It is interesting to note that Metcalfe et al., in a very different context (sealing of access boreholes to a CO_2 storage) recognize that, here again, emplacement (of cement) is the main issue when permeability performance is discussed. More generally, knowledge transfer from the oil and gas industry to that for a waste repository is the topic of Groff et al. The issue of borehole plugging (in the context of a nuclear waste repository) was discussed also by Karvonen and Hansen, who discussed closure plans for the 58 existing investigation boreholes drilled in Olkiluoto Island. The sections of the borehole are filled with dense bentonite to ensure water tightness and the rest of the hole can be filled with concrete, without tightness requirements. In 2013, many lessons for future R&D needs were drawn from over-coring of a borehole plug in which materials (both bentonite and concrete) were installed in 2005.

The sand/bentonite element of the GAST test in Opalinus clay is 8-m long and 3-m in diameter (Spillmann et al.). The permeability requirement was a 10^{-18} m^2; and a corresponding average 1.7 t/m^3 dry density was chosen as target value, with a minimum of 1.6 t/m^3 in locations where compaction cannot be done efficiently. In the FE test (Garitte et al. (b)), both kinds of bentonite blocks (with high and low water contents, respectively) achieved a 1.78-t/m^3 dry density (a higher density can be reached, but each block density is characterized by an equilibrium relative humidity: in particular, a stable block is difficult or impossible to build when % RH is larger than 70%). A granulated bentonite mixture (GBM) is used to backfill the tunnel. An emplacement dry density of 1.45 t/m^3 was targeted and reached.

For other reasons, emplacement also was an issue in the test of a vertical shaft seal performed in the Bartensleben salt mine in Germany (Kreienmeyer et al.). The seal concept implied gravel and asphalt and/or bitumen; the setting temperature was 190°C, raising health and safety concerns. A test in a 12-m^2 x 6-m sealing element proved the technical feasibility of hot asphalt emplacement.

PRESSURES AND FLUIDS

The Darcy law, when applied to a bentonite seal, stipulates that the flow rate of a viscous fluid through the seal is proportional to the pressure gradient and inversely proportional to the fluid viscosity. However, which fluid and which pressures must be taken into account are not always easy to determine. Spillmann et al., when designing the GAST test, take into account both water flow (from the repository access) and gas flow (from the repository). Hart et al. proved that liquid flow through a shaft seal first is downward, as brine permeates slowly to the repository until full saturation is reached after ≈ 41 000 years: after this first period, brine is squeezed out from the repository, whose creep closure rate is $\approx 10^{-4}$/yr. The travel-time indicator was judged useful in this context.

GENERAL COMMENTS

An impressive set of tests were presented. They include the DOPAS Experiments FSS, EPSP, DOMPLU, POPLU, ELSA, REM and similar field experiments, the FE and GAST projects. Dixon et al. described the Tunnel Sealing Experiment (TSX) in 1997-2007 and the post-closure Enhanced Sealing Experiment (ESP) 2009-2016 (ongoing), performed in a granitic pluton within the Canadian Shield.

Difficulties were met: *"There have been some problems with water leakage into sensors during high pressure tests"* (Svoboda et al.); "*The saturation process was interrupted by a leakage event"* (Spillmann et al.); and "*Despite the fact that the plug was installed with the highest possible care, a full disconnection* [between the outer gallery and the sealing element] *could thus not be achieved"* (Garitte et al.(a)).

Despite these difficulties, which are unavoidable in environments in which high water pressure is involved and in which many cables cross the concrete plugs, the tests where highly successful, and the quality of measurement and data acquisition was high. Holt et al. (a) proved that an extensive measurement system can be used and that tests at full scale (with respect to space) are possible. The Rapporteur's opinion is that, among various issues, bentonite emplacement and emplacement quality assurance appear as two of the most demanding requirements for effective sealing of a repository.

Time scale is probably the main issue for hydraulic plugs, and the bentonite seal in the plugs. The seals play an active role during the time period from full saturation until the canister degradation (varies depending on concept 10 000 years- over 100 000 years). Saturation is a slow process and during that time the information gathered from plugs and seals is important to be able to get information on processes influencing the behaviour. Only a few if any natural analogues are available (Wilson et al.) and "*Patience is needed*." to be able to get results from hydraulic behaviour (oral presentation Bosgiraud). In such a context, the fact that the remarkable Experiment TSX, which started 20 years ago (Dixon et al.) cannot be reached any longer due the closure and flooding of AECL URL in Manitoba, is unfortunate from the whole waste community point of view. DOPAS proved that, from a geometrical point of view, tests at full scale are possible, an important result from the perspective of industrialisation of the sealing process. From a temporal point of view, testing the bentonite behaviour at full scale cannot be done in realistic way. As diffusive processes are expected to play a major role, a supporting test performed at a smaller geometrical scale should imply much shorter durations. However, "*Even for the metric scale experiment* (REM, by Andra, Pasteau et al.*), the full resaturation time was estimated to be about 30 years*" (Rübel) and "*upscaling is a major concern*" while the material specifications may change due the different emplacement methods and several iteration rounds are needed (Foin and Bosgiraud) — i.e., the processes might not be the same when long periods of time are considered: "*The relevant processes are rather slow and exceed the operational life time of the DOPAS demonstrators.*" (Hart et al.)

The main answer to this challenge is the Safety Case. The Safety Case includes a description of how the disposal works and an estimate of the possible nuclides fluxes outside the repository, together with their consequences for human beings and the environment. The weight of each parameter or process is discussed; weaknesses are identified; the needs for further scientific advances can be emphasized; and the significance of remaining uncertainties can be assessed (Trpkošova et al., Hart et al., Jobmann and Herold, Rübel, Reijonen et al., Crawford et al.).

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Wilson J., Benbow S., Metcalfe R., Leung H. *Reactive transport modelling of bentonite shaft seals under hypersaline conditions.*

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4. DOPAS 2016 ORAL SESSIONS

In the following chapters (5 through 12) the session agendas and presentation titles are provided with the extended abstracts submitted for DOPAS 2016 Seminar. The oral presentations and posters are available at DOPAS 2016 public web and the links to the documents are available for each Session separately. Session names and chair and co-chair with a short CV are presented in the beginning of each chapter.

Figure 4-1. The DOPAS 2016 audience

5. DOPAS 2016 Seminar Session 1

Session 1 provided an introduction to the roles of full scale sealing demonstrations and in development of disposal concepts.

Chair: Johanna Hansen is R&D coordinator at Posiva Development, Finland and she is a system responsible for Closure of disposal facility. She has M.Sc. in Geology and Mineralogy from Åbo Akademi University in Finland. She has been working for over 15 years at Posiva with site investigations, and development of the disposal concept (both cementitious and bentonite materials aspects and Posiva) and she is the DOPAS Project Coordinator and WP7 Leader. She was also the chair of the DOPAS 2016 Seminar.

Co-chair: Matt White is a Principal Consultant with Galson Sciences, United Kingdom. He has a Ph.D. in Geology (Scaled Analogue Modelling of Tectonic Structures). Matt has provided consultancy support to radioactive waste disposal projects for 23 years, including repository design, requirements management, monitoring, safety assessment, site characterisation and waste packaging amongst other subjects. In the DOPAS Project he has supported the development of the design basis and led the editing of work-package-level summary reports.

Session 1 Schedule and direct links to the DOPAS 2016 Session 1 presentations

0900-0910	Opening of the DOPAS 2016 Seminar	Johanna Hansen, DOPAS coordinator *Posiva Oy, Finland*
http://www.posiva.fi/files/4140/1.1_DOPAS_2016_DOPAS_opening.pdf		
0910-0920	Welcome from Posiva	Erkki Palonen, Corporate Adviser *Posiva Oy, Finland*
http://www.posiva.fi/files/4141/1.2_Palonen_DOPAS_WELCOME_TO_POSIVA.pdf		
0920-0940	Programme status in radioactive waste management and strategic evolution in support to R&D	Christophe Davies, Project Officer *European Commission, Belgium*
http://www.posiva.fi/files/4137/1.3_EC_at_DOPAS_Seminar_2016_-_C._Davies.pdf		
0940-1010	Role of demonstrations for a spent fuel repository concept	Erik Thurner Director, International Relations *SKB International, Sweden*
http://www.posiva.fi/files/4138/1.4_Role_of_demonstration_Dopas_conference_2016_final_Erik.pdf		
1010-1040	Overview of the DOPAS Project	Johanna Hansen, DOPAS Coordinator *Posiva Oy, Finland*
http://www.posiva.fi/files/4170/1.5_Overview_of_DOPAS_project_Johanna_Hansen.pdf		

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6. DOPAS 2016 Seminar Session 2

Session 2 integrated the outcomes from the DOPAS Project including development of the design basis for plugs and seals, lessons learnt from construction of plug and seal demonstrations as well as performance assessment of plugs and seals.

Chair: Marjatta Palmu obtained in 1980 her Master of Science (Technology) in Mining from Helsinki University of Technology (now Aalto) and teacher qualification in 1995. She has worked in geological disposal since 2002 at Posiva Oy, Finland. Her present position is Senior Adviser in Posiva's Development and she is engaged in working with various Euratom FP7 projects in demonstrations and education and training. She has worked with the DOPAS Project from the project preparation phase since 2010 while being the coordinator of the IGD-TP Secretariat FP7 Project SecIGD. She is the Work Package Leader of WP6, Integrating analysis including cross-review of each other's work.

Co-chair: Jan-Marie Potier is a senior expert in radioactive waste management who provides consulting services since his retirement from IAEA and Andra in 2010. As a graduate engineer from Ecole Centrale des Arts et Manufactures in Paris he has over 40 years of professional experience in nuclear fuel cycle activities, mostly uranium mining and radioactive waste management. Mr. Potier acted as the main elicitation expert for the DOPAS Project's external peer review during 2015-2016.

For several years, Mr. Potier worked for the IAEA as Head of the Waste Technology Section, in the Department of Nuclear Energy. Before joining the IAEA, Jan-Marie Potier held several managerial positions within the French National Radioactive Waste Agency, ANDRA, including the position of Technical Director.

Session 2 Schedule and direct links to the DOPAS 2016 Session 2 presentations:

1110-1130	Objectives and main outcomes from the DOPAS full-scale demonstrators: FSS, EPSP, DOMPLU, POPLU and ELSA	DOPAS Experiment leaders in Panel Régis Foin[1], Jiri Svoboda[2], Pär Grahm[3], Petri Koho[4] and Michael Jobmann[5] *[1]Andra,France,* *[2]Czech Technical University, Czech Republic* *[3]Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden* *[4]Posiva Oy, Finland* *[5]DBE TECHNOLOGY GmbH (DBE TEC), Germany*
http://www.posiva.fi/files/4146/2.1_Experiment_summaries_SHORT-PR.pdf		
1130-1200	Design basis of plugs and seals	Matt White[1], Behnaz Aghili[2] and Slimane Doudou[1] *[1]Galson Sciences Limited, United Kingdom* *[2]Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden*
http://www.posiva.fi/files/4142/2.2_White_design_basis.pdf		

1200-1230	Progress on the design and implementation of plugs and seals in the DOPAS Project	Jean-Michel Bosgiraud[1], Matt White[2] and Slimane Doudou[2] [1]*Andra, France* [2]*Galson Sciences Limited, United Kingdom*
http://www.posiva.fi/files/4143/2.3_JMB_Key_Learnings_on_Design_Implementation_of_Plugs_Seals_-_Session_2.pdf		
1400-1425	Performance assessment of plugs and seals	André Rübel, *Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Germany*
http://www.posiva.fi/files/4144/2.4_DOPAS_seminar_ruebel.pdf		
1425-1450	Application of lessons learned during the DOPAS Project to less advanced waste management programmes – Case study: Radioactive Waste Management Ltd	Dean Gentles[1], Wolfgang Kickmaier[2], Matt White[3], Slimane Doudou[3] and Alastair Clark[2] [1]*Radioactive Waste Management Limited, United Kingdom* [2]*McCombie, Chapman, McKinley Consulting, Switzerland* [3]*Galson Sciences Limited, United Kingdom*
http://www.posiva.fi/files/4145/2.5_Gentles_DOPAS_Seminar_-_Application_of_Lessons_Learned.pdf		

Design Basis of Plugs and Seals: Summary of WP2 of the DOPAS Project

Matt White[1], Behnaz Aghili[2] Slimane Doudou[1]

[1]Galson Sciences Limited, UK
[2]SKB, Sweden

Work Package 2 (WP2) of the DOPAS Project was focused on the development of the design basis for the plugs and seals. This paper provides a summary of the main results from WP2. These relate both to the design basis methodology and the requirements on plug and seal performance. The work included identification of the safety functions of the reference plugs and seals conceptual designs, and the design specifications for the experimental detailed designs. Detailed requirements on plugs and seals include those related to the curing temperature of the concrete, the hydraulic conductivity of the sub-system components including the density of bentonite components, the compressive strength of concrete components, and the pH of concrete pore water. The work in WP2 has been used to develop generic guidance on the development of the design basis in terms of a DOPAS Design Basis Workflow. A key observation is that requirements are developed in parallel with designs rather than as a sequential process.

1 Introduction

The Full-Scale Demonstration of Plugs and Seals (DOPAS) Project is a European Commission programme of work jointly funded by the Euratom Seventh Framework Programme and European nuclear waste management organisations (WMOs). 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 focuses on tunnel, drift, vault and shaft plugs and seals for clay, crystalline and salt rocks:

- Clay rocks: the Full-scale Seal (FSS) experiment, being undertaken by Andra in a 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 at the Josef underground research centre and underground laboratory in the Czech Republic, the Dome Plug (DOMPLU) experiment being undertaken by SKB and Posiva at the Äspö Hard Rock Laboratory in Sweden, and the Posiva Plug (POPLU) experiment being undertaken by Posiva, SKB, VTT and BTECH at the ONKALO Underground Rock Characterisation Facility 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.

The French, Czech and Finnish experiments were designed and constructed during the DOPAS Project. The Swedish experiment was started prior to the start of the Project. The German tests focus on the early stages of design basis development and on demonstration of the suitability of designs through performance assessment studies and laboratory testing, and will feed into a full-scale experiment of prototype shaft seal components to be carried out after DOPAS.

Work Package 2 (WP2) of the DOPAS Project was focused on the development of the design basis for the plugs and seals. This paper provides a summary of the main results from WP2. These relate both to the design basis methodology and the requirements on plug and seal performance.

2 Objectives and Approach to WP2 of the DOPAS Project

The main objective of WP2 of the DOPAS Project was to describe the safety functions, the designs, and the design basis of plugs and seals considered in the Project. This included an analysis and discussion of the differences between the design bases for plugs and seals in different repository concepts, focusing on the safety functions performed by each plug and seal, and how these impact on the more detailed requirements.

A further objective was to use the learning from the development of the design bases to provide general guidance on the development of a design basis in the context of repository plugs and seals. In particular, lessons were drawn on the iterative development of the design basis for plugs and seals in parallel with development of the design, as well as the use of hierarchical structures to describe the design basis. This includes the strategies used to demonstrate compliance of the reference designs with the design basis, and in particular with the safety functions captured in the design basis.

The design basis for each of the plugs and seals considered in the DOPAS Project was collated using a bottom-up approach, i.e. no rigid structure was applied during the work, which was approached by extending existing information. This bottom-up approach had the benefit of responding to differences in the manner in which the design basis is developed and/or presented in different programmes.

The collation of the design bases and the development of guidance on the development of the design basis was undertaken in four stages, each one associated with a specific DOPAS Project WP2 task:

- Task 2.1: Design Basis. Collation of the design basis for each plug and seal considered in the DOPAS Project (White *et al.*, 2014).
- Task 2.2: Reference Designs. Documentation of the conceptual designs of the plugs and seals considered in the DOPAS Project (White and Doudou, 2014).
- Task 2.3: Strategies for Demonstrating Conformity of Reference Designs to the Design Basis. Identification and description of the different strategies that are envisaged by WMOs carrying out the DOPAS Project experiments to demonstrate compliance of the designs to the design bases (White and Doudou, 2015).
- Task 2.4: Final Reporting of WP2. In this task all of the WP2 results were compiled in one final report and the guidance on the development of the design basis was developed and presented (White and Doudou, 2016).

3 Background to the Design Basis

3.1 Definition of the Design Basis

In the DOPAS Project, a design basis is defined as the set of requirements and conditions taken into account in design. This definition is consistent with approaches to systems engineering and requirements management (e.g. NASA, 1995; and Robertson and Robertson, 1999). 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.

In DOPAS, the requirements contained in the design basis of plugs and seals are described in terms of the following hierarchy:

- 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.
- System requirements: The requirements on the disposal system that result from adoption of a specific conceptual design, 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.
- Sub-system requirements: A list of the functions that the components of the selected plug/seal design must provide and the qualities that these components must have.
- Design requirements: Statements, usually expressed qualitatively, describing the qualities or performance objectives for plug/seal components.
- Design specifications: A list of quantitative statements describing the requirements on plug/seal components (e.g., their thermal, hydraulic, mechanical, chemical and gas performance; 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.

This approach is consistent with, although slightly modified from, structures used by Posiva and SKB in production reports describing the KBS-3V system (Posiva, 2012; SKB, 2010), and is also consistent with the Vee Model developed by Forsberg and Mooz (1991). At all levels, the design basis includes requirements and the conditions under which these requirements must be met.

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 solution. 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 designs may lead to an updated reference design basis.

3.3 Compliance of Designs with the Design Basis

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 its purpose. It is usually much more difficult (and much more important) to validate a system than to verify it. Strictly speaking, 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 (i.e., the repository system level).

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

- Full-scale Testing: Full-scale testing is the main strategy adopted by WMOs to compliance demonstration of plugs and seals. Full-scale experiments include demonstration of technical feasibility, tests of performance, and combined technical feasibility and performance tests.
- Quantitative Approaches to Compliance Demonstration: The German programme has developed a quantitative approach to compliance demonstration in which the loads on a

structure are compared to the ability of a structure to perform under the induced loads, with uncertainty accounted for by the application of quantitative performance criteria modified to account for uncertainty and to provide an additional safety margin.

- Construction Procedures: WMOs have different approaches to describing the use of construction procedures for compliance demonstration. Some describe construction procedures as an important element of compliance demonstrations, and others consider it to be part of quality control during repository implementation. In any case, the focus of quality control relies to a large extent on the practical experiences gained during "compliance demonstration".
- Monitoring: WMOs have different approaches to the use of monitoring as part of compliance demonstration strategies for plugs and seals. Some WMOs have not made firm decisions on how to monitor repository plugs and seals (e.g., SKB), while others are considering monitoring of repository plugs and seals (e.g., through instrumentation) to provide for compliance demonstration (e.g., Posiva).

4 The Design Basis of the DOPAS Plugs and Seals

4.1 Safety Functions and Conceptual Designs

4.1.1 The Safety Functions and Conceptual Designs of the DOPAS Plugs and Seals

FSS Experiment Design Basis

The safety functions of the drift and ILW disposal vault seal are:

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

The main objective of the FSS experiment was to develop confidence in, and to demonstrate, the technical feasibility of constructing a full-scale drift or ILW disposal vault seal. As such, the experiment was focused on the construction of the seal, and the materials were not saturated or otherwise pressurised. Other experiments that investigate saturation phenomena (e.g., the REM experiment) were undertaken by Andra in parallel with the FSS experiment.

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

EPSP Experiment Design Basis

The safety functions of tunnel plugs in SÚRAO's reference design are to:

- Separate the disposal container and the buffer from the rest of the repository.
- Provide a safe environment for workers.
- Provide better stability of open tunnels adjacent to backfilled disposal tunnels containing emplaced waste.

EPSP is an on-going experiment of a tunnel plug, with the focus of the experiment being on development of fundamental understanding of materials and technology, rather than testing of the reference design. This is because the Czech geological disposal programme is in a generic phase and designs are at the conceptual level. EPSP consists of a pressure chamber, an inner concrete plug, a bentonite zone, a filter, and an outer concrete plug. Concrete walls were used to facilitate emplacement of the experiment. The experiment has been pressurised with air, water and slurry.

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

DOMPLU Experiment Design Basis

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

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

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

POPLU Experiment Design Basis

In Posiva's reference concept the deposition tunnel plug and backfill are considered together as "sealing structures of deposition tunnels". The safety functions of the sealing structures 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. The reference design for deposition tunnel plugs in Posiva's concept is the same as SKB's (i.e., the dome-shaped design).

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

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

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

ELSA Experiment Design Basis

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

The reference concept for disposal of spent fuel, high-level waste (HLW), ILW, graphite and depleted uranium in Germany is based on a repository design for the Gorleben salt dome. The Gorleben repository concept envisages two shaft seals, one in each shaft, and four drift seals. The primary safety function for shaft and drift seals is to provide a sufficiently low hydraulic conductivity to avoid brine paths into the repository and the movement of radionuclides out of it. Work in the DOPAS Project has focused on shaft seals.

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

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

4.1.2 Impact of Host Rock on the Design Basis

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

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

4.2 Design Specifications

The full design basis for each experiment includes numerous design specifications, which form the basis for the detailed designs of the experiments. Many of these specifications are common to several of the experiments. These specifications can be considered in terms of thermal, hydraulic, mechanical, chemical, gas and radionuclide transport processes. Some key requirements include:

- Thermal Requirements: In the DOPAS design bases, requirements on the maximum curing temperature of concrete components of plugs and seals are specified to limit the development of cracks owing to thermal stress development during hydration of the concrete. For example, the maximum temperature of the concrete and shotcrete containment walls in FSS shall not exceed 50ºC. The DOMPLU design basis requires that cooling pipes shall be installed and cooling of concrete shall be performed from the start of concreting. A requirement for DOMPLU that the temperature of the concrete during concrete hydration shall not exceed 20ºC was also set.
- Hydraulic Requirements Hydraulic requirements have been specified for all plugs and seals in the DOPAS Project. For the Cigéo repository concept, the hydraulic conductivity of the seal must be equal to or less than $1x10^{-9}$ m/s, to meet the performance requirement that groundwater flow is predominantly through the host rock. However, the requirement for the swelling clay core currently set in the Andra programme is $1x10^{-11}$ m/s. This is regarded as a realistically achievable value, and the current testing programme is evaluating whether this target value can indeed be met. For the crystalline rock cases, especially the deposition tunnel plug designs developed by SKB and Posiva, the requirement is that the water flow does not lead to piping and erosion of the deposition tunnel backfill and buffer, leading to a hydraulic conductivity of $1x10^{-11}$ m/s being specified for the plug concrete. This is significantly lower than required to manage groundwater flow across the plug. In addition, requirements on the hydraulic performance of plugs and seals also need to consider the overall flux of water across a plug, including through the (concrete) plug, through the contact zone with the host rock, through the EDZ and through the intact host rock. DOMPLU is investigating the water leakage value that can be achieved for a plug. The

target value for the acceptable leakage through the plug is presently adopted to be "as low as possible". Recent calculations predicted an allowed maximum leakage of 0.1 l/min to prevent loss of bentonite from the buffer and backfill (Börgesson *et al.*, 2015). A water leakage rate has not yet been set for deposition tunnel plugs by Posiva but a rate is likely to be set in the future.

- Mechanical Requirements: The strength of plugs and seals is specified to withstand the loads on them, and is typically expressed as the compressive strength of concrete components. The loads can vary owing to the depth of the plug or seal location (e.g., 7 MPa for SKB, SÚRAO and Andra; 7.5 MPa for Posiva). These loads include contributions from the hydrostatic pressures at depth as well as swelling pressures from the backfill.
- Chemical Requirements: Many of the plugs and seals considered in the DOPAS Project are composite structures with concrete components to provide mechanical strength and bentonite components to provide low hydraulic conductivity. For these plugs the concrete pore water is required to be of low pH to reduce any impact on the swelling pressure of the bentonite. This is either expressed as a pH less than 11, or as a calcium silica ratio.
- Gas Requirements: There are no gas permeability requirements for reference designs of plugs and seals represented in the DOPAS Project. However, SKB and Posiva are considering implementation of requirements concerning gas migration through deposition tunnel plugs, because, should gas/oxygen migrate through the plug and backfill into the tunnel deposition holes, canister corrosion could be affected.
- Radionuclide Migration Requirements: Most of the reference designs of plugs and seals represented in the DOPAS Project do not have radionuclide containment or retardation functions. DOMPLU, POPLU and EPSP are designed to hold the backfill in place, although a low leakage rate through these structures is required. FSS represents a hydraulic structure with a low hydraulic conductivity to ensure that any radionuclide migration is through the host rock and not through the seal. For the shaft seal in the German concept, the safety function includes a statement for the seal to "*avoid … the movement of radionuclides out of [the repository]*". This is reflected in the more detailed design basis by inclusion of a requirement to use material with high sorption capacity in the shaft seal components.

5 The DOPAS Design Basis Workflow

Work on the design basis in the DOPAS Project has allowed assessment of current practice with regard to both the process used to develop and describe the design basis, and the content of the design basis of plugs and seals. The design basis is developed in an iterative fashion with inputs from regulations, technology transfer, tests and full-scale demonstrations, and performance and safety assessments. A generic process, the "DOPAS Design Basis Workflow", has been developed for development of the design basis for plugs and seals (Figure 3.1). This workflow is structured to be consistent with a design hierarchy consisting of Conceptual, Basic and Detailed design stages (IAEA, 2001).

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 elements 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 a set of working assumptions for the experiment design specifications, which are used to design the experiment and to assess its performance. The results of full-scale tests provide further support to design decisions, especially 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.

6 Conclusions

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

The design basis is developed in an iterative fashion with inputs from regulations, technology transfer, tests and full-scale demonstrations, and performance and safety assessments. All of these tools have been used to develop an overall “DOPAS Design Basis Development Workflow” consistent with the three design stages (conceptual design, basic design, and detailed design). The development of the design basis is generally undertaken in parallel with development of the design and development of the safety case rather than as a sequential process.

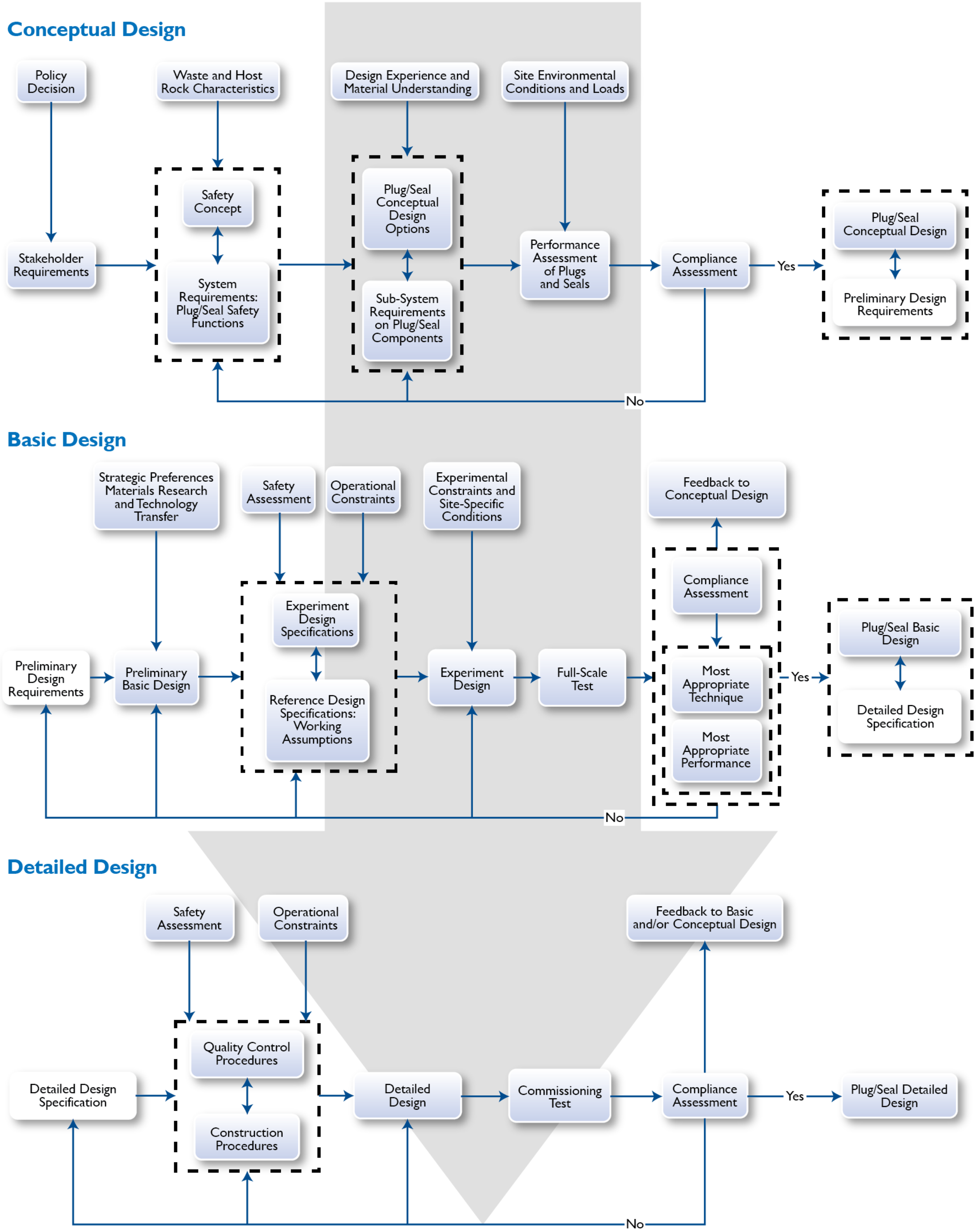

Figure 6-1. The DOPAS Design Basis Workflow.

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Performance assessment of plugs and seals

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This presentation gives an overview on the work in work package 5 on “Performance assessment of the plugs and seals systems” of the DOPAS project. The aims of WP5 were to support the experimental work and the construction of the large-scale sealings by predictive process modelling and to understand the implications of the plugs and seal performance on the overall safety for the whole reference period of a final waste repository of one million years. An important element of this work was to develop justification of model simplifications for long-term safety assessment simulations. This includes the objective to improve the state-of-the-art in process modelling and its abstraction in integrated performance assessment.

1 Introduction

The aim of work package 5 on “Performance assessment of the plugs and seals systems” of DOPAS was mainly twofold. The first aim was the support the planning, construction and experimental work of the large-scale demonstrators by predictive process modelling. Another aim of WP5 was to understand the implications of the plugs and seal performance on the overall safety for the whole reference period of a final waste repository of one million years. An important element of this work was to develop justification of model simplifications for long-term safety assessment simulations. This includes the objective to improve the state-of-the-art in process modelling and its abstraction in integrated performance assessment. More specifically the objectives can be defined as follows:

- simulation of processes and their evolution within individual sealing components,
- predictive modelling to support the design and the construction of the large-scale seals,
- modelling of small and mid-scale experiments performed in WP3 to gain process under-standing,
- identification of the main processes that are relevant and thus to be considered for predicting the short and long-term behaviour of the plug and sealing systems,
- identification of remaining uncertainties and their influence on performance assessment,
- development and justification of conceptual models of plugs and seals for the different disposal concepts and geological environments and
- development and application of the PA methodology and integrated PA models to analyse the system behaviour.

Work-package 5 was divided into the following four different tasks which have a different focus. The task 5.1 is mainly on process understanding and has a very strong link to the experimental work performed in work-package 3 and the other work-packages of the project. The task describes the process on a phenomenological basis and its evolution on different time scales. Suitable process models were identified and improved if necessary to perform process models. The large part of the work performed in this task supported the planning and construction of the experimental work. The first task was the largest part of WP5 regarding work and budget. In the task 5.2, conceptual models were developed striving for abstraction of the process level-work performed in the first. The second task is therefore the link to the third task which finally focused on integrated long-term performance assessment modelling. Integrated models were finally developed and applied in task 5.3 with regard to demonstrate long-term safety and to determine remaining uncertainties and open questions. The task 5.4 was devoted to work package management and reporting.

2 Work performed

This presentation is to summarise the work performed in WP5 and to link to other presentations and posters of the DOPAS seminar were the results are presented in higher detail. Not performed in WP5, but closely related is the work of SKB on predictive modelling for the DOMPLU plug which was performed already prior to DOPAS. The following eight pieces of work have been performed by the organisations participating in WP5 and the related presentations and posters are given in parenthesis.

1. A review performed jointly by Radioactive Waste Management Limited (RWM) and Galson Sciences Limited (GSL) on the state of the art of the treatment of sealing systems in Totals System Performance Assessment (See presentation by D. Galson).

2. The assessment of the water tightness and mechanical integrity of the POPLU experiment by Posiva Oy (POSIVA) to serve as input in the POPLU experiment construction.

3. Predictive process modelling performed by Agence nationale pour la gestion des déchets radio-actifs (ANDRA) of the expected behaviour of the REM experiment, which serves as a metric scale demonstrator of the FSS experiment (See presentation by A. Pasteau et al.).

4. Process modelling performed by DBE TECHNOLOGY GmbH (DBETEC) on the compaction behaviour of sealing materials to be used in the ELSA experiment (See poster by M. Jobmannn et al.).

5. Process modelling of laboratory experiments related to the ELSA experiment to test the mechanical and chemical behaviour of sealing materials by Gesellschaft für Anlagen und Reaktorsicherheit gGmbh (GRS) (See presentation by O. Czaikowski et al. and three posters by K. Jantschik et al., O. Czaikowski et al. and Chun-Liang Zhang).

6. Integration of the processes identified to affect the sealing elements of the ELSA experiment into the integrated performance assessment model by Gesellschaft für Anlagen und Reaktorsicherheit gGmbh (GRS).

7. Process modelling performed by ÚJV Řež a. s. (UJV) for the results from the physical hydraulic model carried out under laboratory conditions as part of the EPSP experiment (See poster by D. Trpkošová et al.).

8. An investigation on options to link demonstrator activities with performance assessment by the use of suitable indicators, performed by Nuclear Research and Consultancy Group (NRG) (See presentation by E. Rosca-Bocancea et al.).

3 Conclusions

Geological disposal of radioactive waste involves isolation and containment of the waste from the biosphere. Containment and isolation can be provided through a series of complementary barriers, e.g. the waste form itself, waste containers, buffer and backfill materials, and the host geology, each of which will be effective over different timescales. As part of the backfilling and closure of a repository, specific parts will have to be closed 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 e.g. may be required to

- isolate emplaced waste from the rest of the underground excavations during the operating phase to limit radiological exposure to the workers,
- support other EBS components until the repository has evolved to its desired state,
- limit groundwater flow and radionuclide migration,
- prevent inadvertent or unauthorized human access.

A variety of modelling tasks has been performed within the work package 5 of the DOPAS project and has been reported in WP5 and WP3 deliverables. The report at hand shortly summarises this work and provide links to all the underlying reports that give more detailed information.

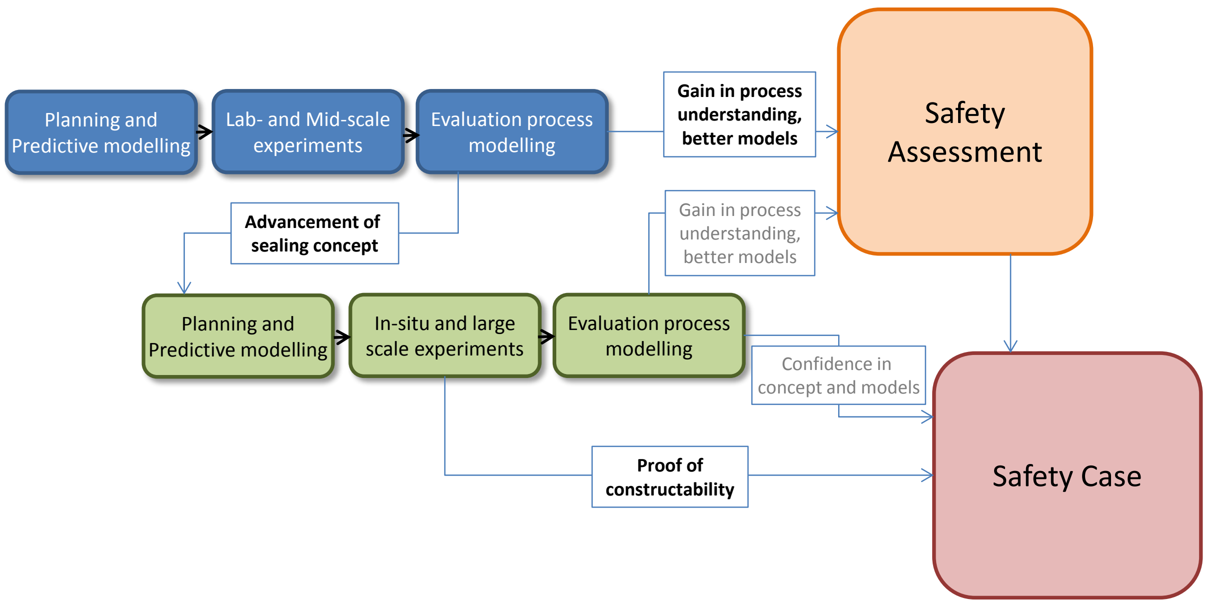

Figure 1: Contribution of work package 5 to safety assessment and the development of the safety case

The DOPAS project and work package 5 contribute significantly to the further development of the safety cases for radioactive waste repositories by bringing forward the plug and sealing concepts in three main host rock types considered in Europe: crystalline rock, clay rock and salt rock. The role of the work package 5 in this contribution is shown in figure 1 and results from predictive and evaluation process modelling of laboratory (blue boxes) as well as in-situ and large-scale experiments (green boxes). The different aspects of the achievements are (white boxes):

- **Gain in process understanding and improvement of models for safety assessment by evaluation process modelling of laboratory experiments:** Process modelling performed of laboratory experiments (work-list number 5 and 7) in work package 5 was able to predict and

interpret the results from laboratory experiments enhancing the confidence in the suitability of the used models to describe the observed processes. The process models were party converted to abstract models that could be included in integrated safety assessment models to achieve a better process representation in future total system performance assessments. Future comparison of the performed predictive modelling on mid-scale experiments (work-list number 3) with experimental results will contribute in the confidence of the validity of the up-scaling of process modelling results from small scale to metric scale.
- **Advancement of the sealing concept:** The process modelling of laboratory and mid-scale in-situ experiments (work-list number 4 and 5) contributed update of the sealing concept and the choice of sealing materials. The predictive process modelling of the in-situ experiment (work-list number 2) directly supported and influenced the layout and construction of the experiment.
- **Confidence in concept and models:** Future comparison of the predictive modelling with experimental results will contribute in the confidence of the validity of the up-scaling of process modelling results from small scale to large scale.
- **Proof of constructability:** All aspects given before jointly contribute to the confidence in the fact that the plugging and sealing systems will develop as planned and will be able to meet their designed function in the overall repository concept.

The high-level design basis of a sealing system (reported in the DOPAS WP2 work) describes the principal safety functions that plugs and seals have to fulfil as part of the overall safety objective of a repository system, typically in a qualitative fashion. The safety functions and performance requirements of the seal which are tested in the DOPAS modelling work of work package 5 are:

- the mechanical stability and
- the hydraulic conductivity, i.e. water tightness of the seal.

The latter is investigated regarding two aspects, either the initial hydraulic conductivity at the time of construction, or its long-term development.

The aim of the process modelling work reported was twofold; the large part of the modelling work was predictive modelling and only a small part was to evaluate experiments. The main use of the predictive WP5 process modelling was to

- design the seals,
- to support construction,
- to predict experiment evolution,
- to predict material behaviour and
- to test models.

The input data which was used in this type of modelling was derived only to a minor part from experiments from WP3 of DOPAS, but mainly from existing data obtained in laboratory experiments of the participating organisations prior to the DOPAS project, and from existing literature. No input was used from the mid and large-scale experiments which are performed within DOPAS. The reason for this is that the main results from the larger scale experiments were not available within the project duration of DOPAS. Even for the mid- or small-scale laboratory experiments, only a minor part of the modelling work was performed to evaluate results of experiments. A large amount of experiments that have been started in DOPAS will be continued beyond the end of the DOPAS project. Therefore, more modelling work is expected to be performed in the future to interpret the results. This work will be reported in company reports of the organisations performing the experiments.

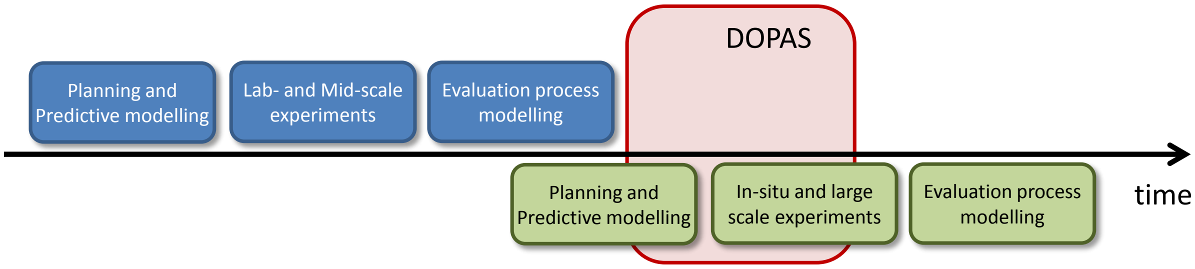

Figure 2: DOPAS in the life-time of the experimental program to investigate plug and seal behaviour

The aspect of DOPAS in the life-time of the experimental program to investigate plug and seal behaviour is further illustrated in figure 2. Even for DOPAS, with 48 months of duration being one of the longest running EU projects, this project can only represent a short section of the long time-span for the iterative process of preparative laboratory work, planning of a large-scale experiment, executing the experiment and finally investigating the results by process modelling. For example, even for the metric scale experiment (REM) by ANDRA (see also work-list number 3), which only acts as a small scale model for the full scale experiment, the full resaturation time was estimated to be about 30 years. Due to the different stages the different experiments were in at the beginning of DOPAS, mostly all parts of the experimental cycle were covered by DOPAS, except the evaluation process modelling of a large-scale experiment. While on the one hand, the ELSA experiment still was in an early stage of laboratory and mid-scale experiments, on the other hand the installation of the DOMPLU experiment was already ongoing. Due to this temporal shift, different stages of the experimental process were investigated in DOPAS.

Finally it can be concluded that the process modelling work performed in work package 5 of DOPAS has significantly contributed to the preparation and execution of the experiments and has helped to interpret the obtained results of some of the experiments. Since many of the experiments are not finished at the end of DOPAS, more updated process modelling is expected in the future to investigate the experimental results and to confirm predictive modelling. This work will be reported in company reports of the organisations which performed the work listed above.

Application of Lessons Learned for Less Advanced Waste Management Programmes During the DOPAS Project – Case Study: RWM

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[2]McCombie, Chapman, McKinley Consulting, Switzerland
[3]Galson Sciences Limited, United Kingdom

The DOPAS project ("Full-Scale Demonstration Of Plugs And Seals") aims to improve confidence in the industrial feasibility of plugs and seals in geological disposal facilities (GDF). This includes demonstrating different design options at full-scale, under realistic boundary conditions and monitoring the evolution of the plug and seal system. The project is built around a set of full-scale demonstrations, laboratory experiments and performance assessment studies, and is jointly funded by the Euratom Seventh Framework Programme and European nuclear waste management organisations.

A large amount of information has been generated as part of the DOPAS project, which is of benefit to the UK implementer, Radioactive Waste Management Limited (RWM), which should be considered at the early stages of plug and seal design development. One of the main objectives of this paper is to show how such learning can be applied within RWM's programme. A similar approach could be applied by other less advanced waste management programme. The paper includes lessons learned from Safety Functions and Requirements, Conceptual Designs, Design Assumptions and Technologies and also discusses how the DOPAS Project has contributed to the advancement of the RWM generic programme.

The project provided direct input to determining when, and at what level of detail, plugs and seals should be developed as part of the UK programme, providing feedback on how the design data sheets and Disposal System Technical Specification (DSTS) could be updated.

Here the main findings are presented, but RWM internal reports address specific topics in more detail. Thus, for this paper and in the context of the DOPAS project, we focus on those issues which might be relevant for other countries in a similar position to the UK programme.

1 Introduction

RWM has been established, in the UK, as the delivery organisation responsible for the implementation of a safe, sustainable and publicly acceptable geological disposal facility (GDF), for the UK's higher activity wastes. In order to identify potential sites, where a GDF could be located, RWM and the UK Government are developing a voluntarism approach based on working with communities that are willing to participate in the siting process. In order to progress the programme for a GDF, in the absence of a specific site, RWM has developed generic illustrative designs for three different host geologies:

- Higher strength rock (e.g. Crystalline Rocks)
- Lower Strength Sedimentary Rock (e.g. Clay)
- Evaporite (e.g. Salt)

The concepts which make up RWM's illustrative designs [i], are derived from international concepts which are supported by extensive research and development, and have been subject to detailed safety assessment, regulatory scrutiny and international review. The illustrative designs form part of RWM's generic disposal system safety case (DSSC). The generic DSSC is used for initial dialogue with regulators and communities, as well as to support waste packaging advice through disposability assessments for waste producers.

Figure 1 below shows how RWM intend to progress from its current generic phase through to implementation of a GDF.

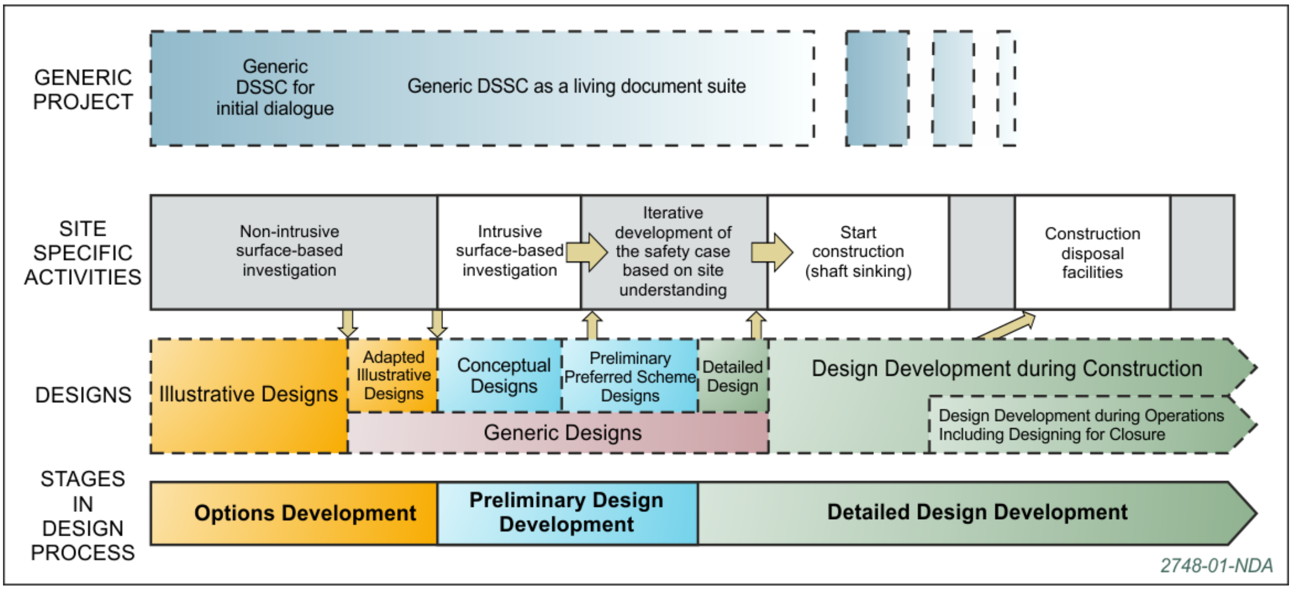

Figure 1: RWM Engineering Design Development Stages

Due to RWM's current generic phase of development, the design of plugs and seals within the illustrative designs does not need to be detailed, in order to meet the needs of the generic DSSC. However, now that tested designs exist, RWM's illustrative designs could be updated to incorporate the learning from the DOPAS project.

1.1 Scope

The DOPAS project ("Full-Scale Demonstration Of Plugs and Seals") aims to improve confidence in the industrial feasibility of plugs and seals in geological disposal facilities (GDF). This includes demonstrating different design options at full-scale, under realistic boundary conditions and monitoring the evolution of the plug and seal system. The project is built around a set of full-scale demonstrations, laboratory experiments and performance assessment studies, and is jointly funded by the Euratom Seventh Framework Programme and European nuclear waste management organisations. Comprehensive background on the DOPAS project can be found in the final reports of the project (and references therein) and the proceedings of this seminar.

The DOPAS project is focused on the development of plugs and seals for disposal tunnels, drifts, disposal vaults and shafts in crystalline rocks (broadly equivalent to RWM's higher strength rock), clay rocks (broadly equivalent to RWM's lower strength sedimentary rock) and salt rocks (broadly equivalent to RWM's evaporite rock). These include:

- *Crystalline Environment*: experiments related to plugs in horizontal disposal tunnels, including the Dome Plug (DOMPLU) experiment being undertaken by SKB at the Äspö Hard Rock Laboratory (Äspö HRL) in Sweden, the Posiva Plug (POPLU) experiment being undertaken by Posiva at the ONKALO Underground Rock Characterisation Facility (URCF) in Finland, and the Experimental Pressure and Sealing Plug (EPSP) experiment being undertaken by SÚRAO and the Czech Technical University (CTU) at the Josef URC and underground laboratory in the Czech Republic.

- *Clay Environment*: the Full-scale Seal (FSS) experiment, being undertaken by Andra in a surface facility at St Dizier in France, is an experiment on the construction of a drift and ILW disposal vault seal.
- *Salt Environment*: tests related to seals in shafts as part of the development of shaft closure concepts (ELSA) experiment, being undertaken by DBE TEC together with the Technical University of Freiburg and associated partners, complemented by laboratory testing performed by GRS in Germany.

This paper captures the outcomes of *DOPAS Lessons Learned Project*, summarising the relevant benefits to RWM's programme from the DOPAS project, and more generally, other waste management programmes. The work, undertaken collaboratively by RWM, MCM and Galson Sciences, is based mainly on DOPAS Work Package (WP) 2 (Requirements and Design Basis), WP3 (Design and Technical Construction Feasibility) and WP4 (Appraisal of plug and seal system's function) and the additional experience gained throughout DOPAS project meetings and workshops.

2 Specific aspects of the RWM programme

In the following section, the main aspects of the RWM programme for which specific lessons have been identified are summarised briefly. It should be noted that, although the basis for this work was for the UK programme, currently in a generic phase, similar conclusions could be drawn by other waste management organisations at an equivalent early stage of repository implementation.

2.1 Disposal system specification and design basis

As part of the project, RWM's generic Disposal System Technical Specification (DSTS), which describes the requirements on the disposal system, together with a justification for each requirement, [ii] was reviewed, with regards to plugs and seals. Due to the generic nature of the DSTS, the detail on plugs and seals is at a relatively high level, where the types of plugs and seals and their safety functions, are discussed in a generic manner.

The following types of plugs and seals can be recognised, with some having multiple functions and therefore recognised by location, and some having a specific (singular) function: High-heat Generating Waste (HHGW), Disposal Tunnel Plugs; Low-heat Generating Waste (LHGW), Vault Seals; Mechanical Plugs; Shaft Seals; Borehole Seals; and Human Intrusion Plugs. Suggestions for revising the RWM specific descriptions of plugs and seals, in the DSTS, can be taken forward at an appropriate stage in the future.

Significant work on the development of the design basis for plugs and seals was undertaken in the DOPAS project. It was recognised that this work was relevant to general processes used to develop GDF designs. Key lessons included:

- The design basis incorporates requirements and the conditions under which these must be met.
- The design basis should include a description of how compliance will be demonstrated.
- Requirements are developed in parallel with designs; each level in the requirements hierarchy provides requirements for successively more detailed designs.

Within the DOPAS project, a *Design Basis Workflow* [iii] was created which describes a generic process for the parallel development of a design basis and actual designs for plugs and seals. The design is developed in an iterative manner, with input from regulations; technology transfer; tests

and full-scale demonstrations; and performance and safety assessments. The majority of these activities are undertaken in parallel and therefore close coordination of interfaces is required.
It has to be recognised that the Workflow is applicable to all GDF design work and is a useful tool for planning activities, in particular understanding the level to which designs need to be developed at each stage in implementation of geological disposal. It also addresses the ability to test and confirm the reliability of the construction (e.g. define the tolerance required before safety functions are undermined). At the current stage of the UK Programme, not all design work has to be undertaken to the same level of detail. However, an understanding of the basic designs of plugs and seals may be necessary to undertake cost and programme analyses for illustrative designs, which may require drawing on the more detailed work available through the DOPAS project.

2.2 Conceptual designs of plugs and seals

The DOPAS project provides a sound basis for the first stage of generic design development. However, the plug and seal designs developed in the DOPAS project are clearly related to the status of specific programmes – very detailed designs for advanced programmes such as in Sweden and Finland or more experimental designs such as in the Czech Republic. Common to all is that plugs and seals are composite structures with several components, each with specific functions. The designs are dependent on the host rock, the overall disposal concept, the waste types and also respond to requirements (including stakeholder requirements). The conceptual design options developed during the DOPAS project could be, with modifications, applied in the early stages of the RWM plug and seal design development, recognising that, at an early stage of a programme (e.g. host rock not defined and specific host rock parameters not available), going further than a preliminary conceptual design is not necessary. A stepwise approach “What is needed, When and at What level of detail” will be defined and communicated. Considering the fact that the DOPAS project addresses mainly disposal tunnel plugs and seals based on the well-advanced Nordic concept (DOMPLU and POPLU) and the French FSS (vault sealing and plugging for ILW), it is clear that further input from ongoing work outside DOPAS, should also be analysed for its benefit to the UK programme. Detailed work on plugs and seals, such as gas permeable seals, alternative designs and construction techniques were presented, for example, at the Performance of Engineered Barriers (PEBS) conference in Hannover in 2014 [e.g. iv, v, vi, vii, viii, ix].

The current draft of the Geological Disposal Facility Designs (GDFD) contains a section entitled *Sealing Strategy*, describing the locations and materials used for plugs and seals in higher strength rock, lower strength sedimentary rock and evaporite rock [i]. RWM has produced a database with generic design assumptions to underpin the information in the GDFD. Based on the experience gained within DOPAS, the assumptions made were critically reviewed and proposals for amendments were made, to ensure that the GDFD and the design assumptions are consistent and not in contradiction to the main conclusions drawn by the DOPAS project. The review of the UK illustrative designs identified a need for greater tailoring of design solutions to safety functions. Alternative assumptions were identified for RWM to further consider at a later date. In particular, the specific function for each type of plug and seal needs to be carried through to the next iteration of the design. In addition, DOPAS illustrated the differences between references designs and experimental plug designs. Thus, it is important to specify those elements and functions which are based on the repository conceptual design and those related to the needs of experiments. These different requirements need to be clearly specified and handled in the requirements management system (RMS).

2.3 Geological Disposal Facility (GDF) technology and Engineered Barrier System materials

The DOPAS project demonstrated the feasibility (and practicability) of constructing plugs and seals under almost realistic conditions, providing a *toolbox* of proven and demonstrated technologies for

emplacement & construction of such structures. The solutions provided are, however, specifically tailored to the concepts and specific boundary conditions found or assumed at the repository sites that were focus of these projects e.g. the POPLU experiment.
The design, construction and the selection of suitable materials for plugs and seals is more complex than was originally expected at the start of the project. However, the effectiveness of plugs and seals is governed by a relatively small number of parameters, e.g. pre-existing joints, fractures or other geological connections in the vicinity of a plug; presence and extent of an Excavation Damaged Zone; the rock surface characteristics; or the length of the plug. It should be noted that the relative importance of these parameters and the resulting engineering solutions are dependent on the host rock environment and, even within a specific host rock, the local characteristics at the plug position need to be taken into account. Specifically, for the UK programme, the following aspects should be considered:

- The requirements as formulated in the DSTS are generic, and therefore not site specific. These requirements will be further developed as RWM progresses towards implementation.
- An iterative cycle of design, testing and assessment allows engineering solutions to be developed, based on a realistic design basis, requirements and conditions.
- An integrated view, considering the entire repository system and sub-systems, in addition to operational safety aspects, is required when further developing UK specific plug and sealing systems and / or identifying research needs.
- An integrated approach to capture input from engineering, operational safety and long-term safety teams is also required at an early stage. Detailed assumptions and requirements for all types of plugs and seals have to be systematically included in a RMS.
- Specific materials / components might not be available on an industrial scale in future decades, so it is not sensible to develop detailed designs which are not going to be implemented in the near term, the technology used to construct plugs and seals may also evolve over time.
- The design - construction process should provide flexibility to react to new (or changing) boundary conditions, such as requirements for monitoring.

3 Examples of DOPAS lessons learned linked to RWM functions and associated deliverables

In the following selected examples, DOPAS lessons learned are linked to RWM functions and associated deliverables are presented.

Design	
Functions and deliverables	GDF Design Reports, Engineering Design Manual and supporting procedures, Geological Disposal Facility Design status report
• Design assumptions and design procedures need to be critically reviewed and updated. • Input to the Technical Maturity Analysis, raising the Technical Readiness Level (TRL) of underground designs. • The generic work flow, illustrating the iterative steps from conceptual to detailed design, provides a flexible approach to linking safety functions with design specifications that can be tested via a demonstration programme and Quality Control procedures applied in during disposal operations. • Considering the fact that DOPAS addresses mainly the disposal tunnel plugs and seals based on the well advanced Nordic concept and, with the French FSS, the vault seals and plugs for ILW, it is obvious that further input, from outside of DOPAS, is required for the UK programme.	

• At the current stage of the UK Programme, concentration of effort on conceptual design will guide the R&D programme required for the next years, until a preliminary decision on host rock(s) has been taken. • While further developing a Generic DSS a holistic view is needed; besides disposal tunnel plugs and seals as tested in the DOPAS, other plug types need to be addressed (e.g. gas permeable plugs). • The design - construction process should provide flexibility to react to new (or changing) boundary conditions, such as requirements for monitoring (e.g. development of wireless monitoring system for plugs).

Research	
RWM functions and associated deliverables	Science and Technology Plan, Research Status Reports
• Identification of knowledge gaps. Guidance on the level of detail required and iterative steps during GDF implementation. • The conceptual designs for plugs and seals depend on the host rock environment. The R&D programme and activities related to plugs and seals should reflect the current needs of the implementation programme. Spending resources in developing detailed plugs designs and related materials (concrete formulations) at a generic stage of the programme, without knowing key host rock parameters, is not sensible.	

Disposal System Specification	
RWM functions and associated deliverables	Science and Technology Plan, Research Status Reports, Disposal System Technical Specification
• DOPAS provides a sound basis for the first generic design work. • Consistent use of terms right from the very beginning (and indeed throughout all departments) is extremely important. The development of safety functions and requirements for individual repository elements (e.g. plugs, seals) needs to be integrated within the overall repository system, as specific elements / subsystems influence each other. • A clear time horizon for the performance and related safety functions (e.g. 100 or 300 year operational / open phase of the repository) is required, even at the stage of first conceptual designs.	

Safety Assessment (not a focus of the project)	
RWM functions and associated deliverables	Environmental Safety Case, Operational Safety Case
• Guidance of representation of plugs / seals in post-closure safety assessment. • Approaches to operational safety in other programmes, including mitigation measures employed.	

• DOPAS illustrated specific compliance demonstration strategies, which need to be closely linked to regulatory requirements.

Communications	
RWM functions and associated deliverables	Web-site, Brochures, Information material, Publications
• DOPAS provides comprehensive documentation on the state of the art of plugs and seals. • DOPAS provides a sound basis for the first generic design work and associated communication to the public and other stakeholders. • An active communication via scientific papers, brochures, websites etc. should be initiated, highlighting solutions demonstrated and the active role of RWM in this project. • Use of demonstrations in URLs in defining operational procedures, licensing and commissioning of a GDF.	

4 Conclusions

The DOPAS lessons learned project has demonstrated that plugs and seals are complex structures, which should be recognised in more detail, as the UK programme advances. A wide range of plugs and seals are required, with different operational and post-closure safety functions. RWM's programme could benefit from adopting, through formal change control, a comprehensive set of plugs and seals to cover the design options for the three illustrative GDF designs. This would provide a consistent basis for developing plug and seal designs, leading on from the early generic phase of the programme. The requirements on, and designs of, plugs and seals depend on the geological environment, and different plug and seal types and designs for each type need to be incorporated into the illustrative designs. The R&D programme and activities related to plugs and seals should reflect the current needs of the programme.

The DOPAS project has further developed the design basis and specific designs for a range of plugs and seals relevant to higher strength, lower strength sedimentary and evaporite host rocks. However, the work in the DOPAS project has not considered all types of plugs and seals, for example, there has been no sealing of major water conducting fracture zones. Therefore, RWM will need to undertake further work to develop design solutions for the full range of plugs and seals needed. This should include incorporation of clearly justified conceptual design assumptions with respect to plugs and seals in the illustrative designs; these assumptions could have significant implications for the technical feasibility, safety performance, cost and schedule of a GDF, and should, therefore, be understood within the current generic programme.

Plugs and seals are composite structures, with specific components required to deliver the safety functions. Work in DOPAS has also illustrated a wide range of design options for these components, for example, the bentonite strips applied in POPLU, the filters and delimiters used in DOMPLU, and the mixed pellet/crushed pellet bentonite system employed in FSS.
The DOPAS design basis workflow has been developed from the understanding and experience from the different design approaches used by specific waste management organisations. The workflow is now consistent with the design processes used by all partners, serving as a useful tool in planning GDF design.

An integrated view, considering the entire GDF system and associated sub-systems, is required when further developing UK-specific plug and seal systems and identifying research needs.

Integrated engineering, operational safety, and post-closure safety teams are required to work on such design development.

5 Acknowledgements

In conducting this work, contributions from colleagues at RWM, MCM Consulting and Galson Sciences are gratefully acknowledged. Acknowledgement is also extended to the wider DOPAS Partners and the European Commission, without whom the project would not have been possible.

6 References

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iv de La Vaissière, R., Conil, N., Morel, J., Leveau, F., Gatabin, C., Garcia-Siñeriz, J.L., Habos, H., Rey, M., Piedevache, M., Helminger, B. and Balland, C. (2014). Design and Construction of a Large-Scale Sand-Bentonite Seal in the Meuse/Haute Marne Underground Research Laboratory: NSC Experiment 2014 Proceedings International Conference on the Performance of Engineered Barriers February 6-7, 2014 - Hannover, Germany.

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viii de La Vaissière, R., and Talandier, J. (2014). Interaction between Gas and Bentonite Seals: Small Scale in-situ test in the Meuse/Haute Marne Underground Research Laboratory International Conference on the Performance of Engineered Barriers February 6-7, 2014 - Hannover, Germany Proceedings.

ix Popp, T., Rölke, C. and Salzer, K. (2014). Hydro-mechanical Properties of Interfaces in Sealing Plugs constructed of Bentonite-Block Assemblies International Conference on the Performance of Engineered Barriers February 6-7, 2014 - Hannover, Germany Proceedings.

7. DOPAS 2016 Seminar Session 3

Session 3 presented plugs and seals experiences from past projects or work done for purposes like borehole sealing and underground hazardous waste disposal facilities. The reason for this session was to examine the topic of plugs and seals in broader context and also gain an understanding of how plugs and seals are treated in safety cases.

Chair: Dean Gentles works for the Radioactive Waste Management Limited, United Kingdom – Engineering Department. He is an Engineering Manager with a Master's degree in civil and structural engineering, and is responsible for various aspects of design development during the RWM generic development phase. This position includes consideration of plugs and seals. He is DOPAS Work Package Leader for WP4, Appraisal of plug and seals systems function.

Co-chair: Jiri Svoboda is an Assistant Professor at Czech Technical University in Prague, Czech Republic. He has over 15 years of research experience, with a Ph.D. (Physical and Material Engineering Branch, 2004) and a Master's degree (Structures and Transportation - Geotechnics, 1999) both in Civil Engineering from the Czech Technical University. He is the Experiment Leader for the EPSP in the DOPAS Project.

Session 3 Schedule and direct links to the DOPAS 2016 Session 3 presentations:

1515-1520	Introduction	
1520-1540	Treatment of seals and sealing systems in total system performance assessment	Mark Crawford[1], Dan Galson[1] and Lucy Bailey[2] *[1]Galson Sciences Limited, United Kingdom* *[2]Radioactive Waste Management Limited, United Kingdom*
http://www.posiva.fi/files/4147/3.1_Galson_DOPAS_2016_Presentation_TSPA_for_Seals_V3.pdf		
1540-1600	Full-Scale tunnel and shaft seals: Tunnel Sealing Experiment (TSX) and Enhanced Sealing Project (ESP) at the Underground Research Laboratory (URL) in Canada	D.A.Dixon[1], D.Priyanto[2], J.B.Martino[2], P.Korkeakoski[3], R.Farhoud[4] and K.Birch[5] *[1]Golder Associates Ltd., Canada;* *[2]Canadian Nuclear Laboratories, Canada;* *[3]Posiva Oy, Finland;* *[4]Andra, France;* *[5]Nuclear Waste Management Organization (NWMO), Canada,*
http://www.posiva.fi/files/4148/3.2_Dixon_DOPAS_2016_TSX_ESP.pdf		
1600-1620	The Gas-Permeable Seal Test in the Grimsel Test Site	Thomas Spillmann[1], B. Lanyon[2], R. Senger[3] ,Paul Marschall[1] and Jörg Rüedi[4] *[1]Nagra, Switzerland* *[2]Fracture Systems, United Kingdom* *[3]Intera, USA* *[4]Pöyry, Switzerland*
http://www.posiva.fi/files/4149/3.3_DOPAS2016_Spillmann_etal_-_2.pdf		

1620-1640	Experiences from an *in situ* test site for a sealing element in shafts and vertical excavations in rock salt	Beatrix Stielow[1], Jürgen Wollrath[1], Matthias Ranft[1], Monika Kreienmeyer[2], Thomas Schröpfer[2] and Jan Bauer[2] [1]*Bundesamt für Strahlenschutz (BfS), Germany* [2]*Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE), Germany*
http://www.posiva.fi/files/4150/3.4_Kreienmeyer_DOPAS-2016-MKr-ohne-video.pdf		
1640-1700	Development of a UK approach to sealing deep site investigation boreholes: knowledge transfer from other industries	Francois Groff[1], Nick Jefferies[2] and Simon Norris[3], [1]*Schlumberger, United Kingdom* [2]*Amec Foster Wheeler, United Kingdom* [3]*Radioactive Waste Management Limited, United Kingdom,*
http://www.posiva.fi/files/4151/3.5_Jefferies_development_of_UK_approach_B_230516.pdf		
1700-1715	Posiva plans and experiences for borehole closure	Taina Karvonen[1] and Johanna Hansen[2] [1]*Saanio & Riekkola Oy, Finland* [2]*Posiva Oy, Finland*
http://www.posiva.fi/files/4152/3.6_Posiva_borehole_closure_-_DOPAS_KTAI-EJOH_ver2.pdf		
1715-1730	Conceptual sealing strategy and initial performance assessment for the Chandler Storage and Isolation Facility	Steve Reece *Tellus Holdings, Australia*
http://www.posiva.fi/files/4153/3.7_Reece_FULL_-_Conceptual_Sealing_Strategy_and_Initial_Performance_Assessment_for_the_Chandler_Storage_and_Isolation_Facility_DOPAS_May_2016vB_(FULL_VERSION).pdf		

Treatment of Seals and Sealing Systems in Total System Performance Assessment

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Total System Performance Assessments (TSPAs) for geologic disposal facilities (GDFs) generally assume that plugs and seals perform as expected during "normal evolution" in the post-closure period. In turn, the TSPA calculations show that the disposal system as a whole provides acceptable post-closure safety. Put another way, any intended post-closure safety function(s) of the plugs and seals – principally hydraulic isolation – is assumed to be fulfilled and to contribute to overall safety of the GDF. Uncertainty in seal performance in TSPAs is handled mainly through either parameter values for seal properties or alternative scenarios. Parameters representing seal properties are either conservatively kept constant over time or changed in a stepwise fashion. Changing properties over time are used to account for known, but often poorly constrained, processes. Some TSPAs, particularly those concerned with disposal concepts in low-permeability sedimentary host rock, consider scenarios that explicitly include a situation of poor seal performance. The bounding case of abandonment of a GDF before closure, i.e. before emplacement of final tunnel closures and shaft/access ramp seals, is also included in a number of TSPAs.

1 Introduction

A review has been undertaken to evaluate how sealing systems for deep or geologic disposal facilities (GDFs) have been considered in Total System Performance Assessments (TSPAs). The term TSPA is used here to emphasise the distinction between safety assessments for the performance of GDFs in their entirety and assessments or PAs for seals only, i.e. at a component scale. This review considers published TSPAs for a range of proposed, constructed and operational GDFs.

Given the objective of the review, it was considered desirable to cover as many examples of TSPAs as possible. It should be noted that the example for each country is the last published TSPA; in a number of cases, the TSPA is quite old and may not therefore represent the current programme position. The countries covered in the review and the associated Waste Management Organisation (WMO) and TSPA are listed below by host geological environment for the GDF:

- Crystalline host rock
  - Sweden - SKB SR-Site 2010, updated 2015 (SKB 2015), Spent Fuel (SF).
  - Finland - Posiva TURVA 2012 (Posiva 2012a), SF.
- Sedimentary non-evaporite host rock
  - France - ANDRA 2005 Argile (Andra 2005a,b), SF/high-level waste (HLW)/intermediate-level waste (ILW).
  - Switzerland - NAGRA Entsorgungsnachweis 2002, SGT-E2 (Nagra 2002, Poller et al. 2014), SF/HLW/ILW.

  - Canada, OPG Deep Geological Repository (NWMO 2011), low-level waste (LLW) and ILW.
  - Belgium - ONDRAF-NIRAS SAFIR2 (ONDRAF/NIRAS 2001), SF/HLW/ILW.
- Salt (evaporite) host rock
  - United States - USDOE Waste Isolation Pilot Plant (WIPP) Compliance Certification Application (USDOE 1996), updated 2004, 2009, and 2014, ILW.
  - Germany - GRS Vorläufige Sicherheitsanalyse für den Standort Gorleben – VSG 2012 (Larue et al. 2013, Rubel et al. 2014), SF/HLW/ILW.

2 Summary of Approaches

Overall, TSPA calculations for normal evolution scenarios generally assume that plugs and seals perform "as expected". In turn, the TSPA calculations show that each disposal system as a whole provides acceptable post-closure safety (e.g. SKB 2015, NWMO 2011, USDOE 2009). Put another way, any intended post-closure safety function(s) of the plugs and seals – principally hydraulic isolation – is fulfilled by expected performance and contributes to overall safety.

In reverse, TSPA calculations may be used to set design requirements for plug and seal performance – for example, what hydraulic conductivity is necessary to achieve a certain level of performance (e.g. Nagra 2002), and what levels of performance are achieved during normal evolution – for example, what is the radionuclide flux through a seal (e.g. Andra 2005b).

3 Treatment of Uncertainty

Treatment of uncertainty in seal performance in TSPAs can be categorised using the widely-used three-fold classification of parameter, model and scenario uncertainty (e.g. Crawford and Galson 2009; Figure 3-1). We provide examples of how uncertainty in seal system performance has been accounted for in TSPA via each of these means.

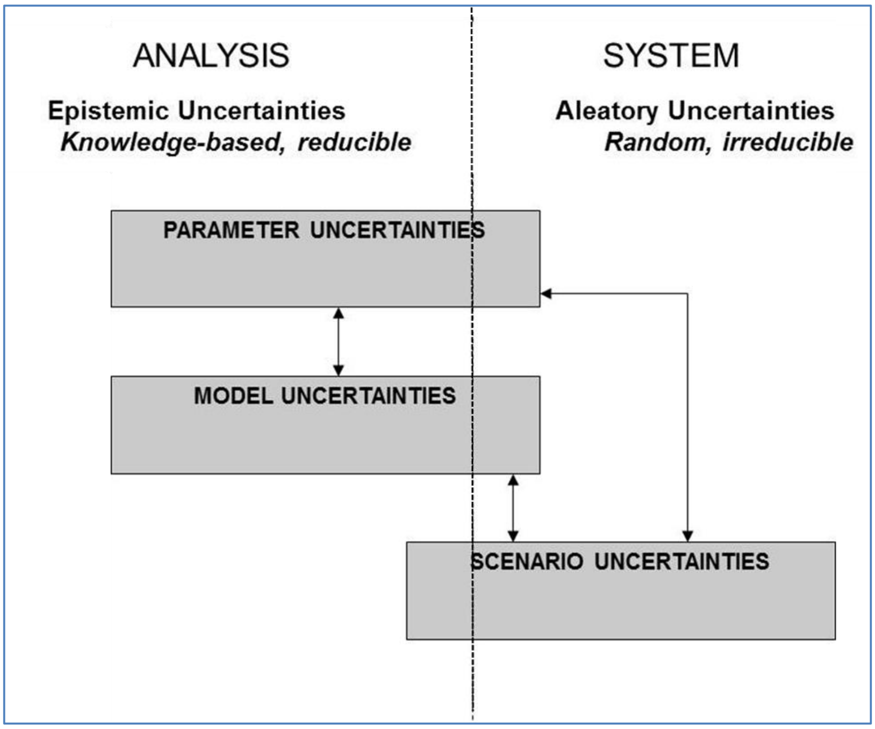

Figure 3-1. Classification and nature of uncertainties in TSPAs (Crawford and Galson 2009).

3.1 Parameter Uncertainty

Both deterministic uncertainty analyses and probabilistic calculations have been used to take account of uncertainty in the properties of seals. For example, the Reference Case groundwater flow modelling in the Finnish TSPA includes a calculation that incorporates a 0.1-m-thick crown space in disposal tunnels with a high hydraulic conductivity (10^{-3} m/s) (Posiva 2012b). The WIPP TSPA is a probabilistic assessment that samples the permeability of a concrete room seal (USDOE 1996; Figure 3-2). The parameter values for the analyses may be based on supporting modelling and/or expert judgement. The properties are either conservatively kept constant over time (e.g. USDOE 1996) or are changed in a stepwise fashion (e.g. Larue et al. 2013). Changing properties over time are used to account for known, but often poorly constrained, processes such as concrete degradation, salt compaction, and clay swelling. The potential for sudden change may drive scenario definition rather than be captured as parameter variation within the same scenario.

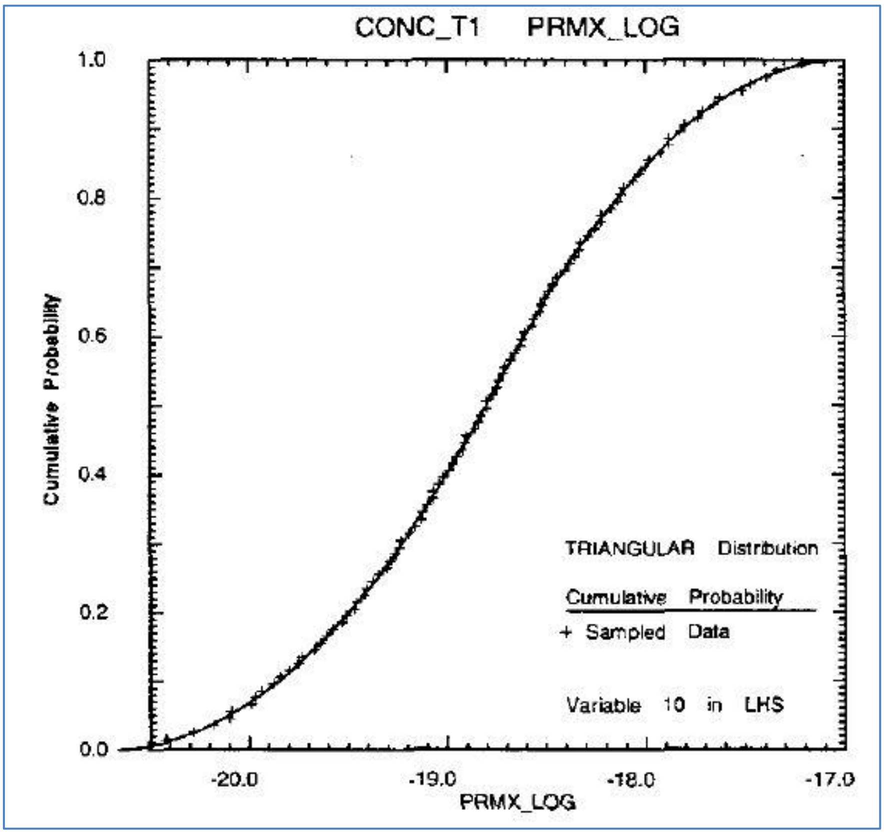

Figure 3-2. Cumulative probability function for the hydraulic permeability of concrete in a panel (room) closure (seal) at the Waste Isolation Pilot Plant (USDOE 1996).

3.2 Model uncertainty

Alternative model configurations or conceptual uncertainty in the modelling of features, events and processes might be captured through sets of analyses specified to address model uncertainty. For example, Poller et al. (2014) used flow modelling to assess the impact of alternative arrangements and performance of seals (Figure 3-3). The flow calculations were then used in a radionuclide release and transport model and biosphere dose conversion factors applied to calculate individual effective dose rates. However, no instances of “top-level” TSPA modelling of actual processes leading to changes of plugs and seal properties during a calculation were found in the review. For example, coupled processes relevant to seal system performance are not directly accounted for in TSPA.

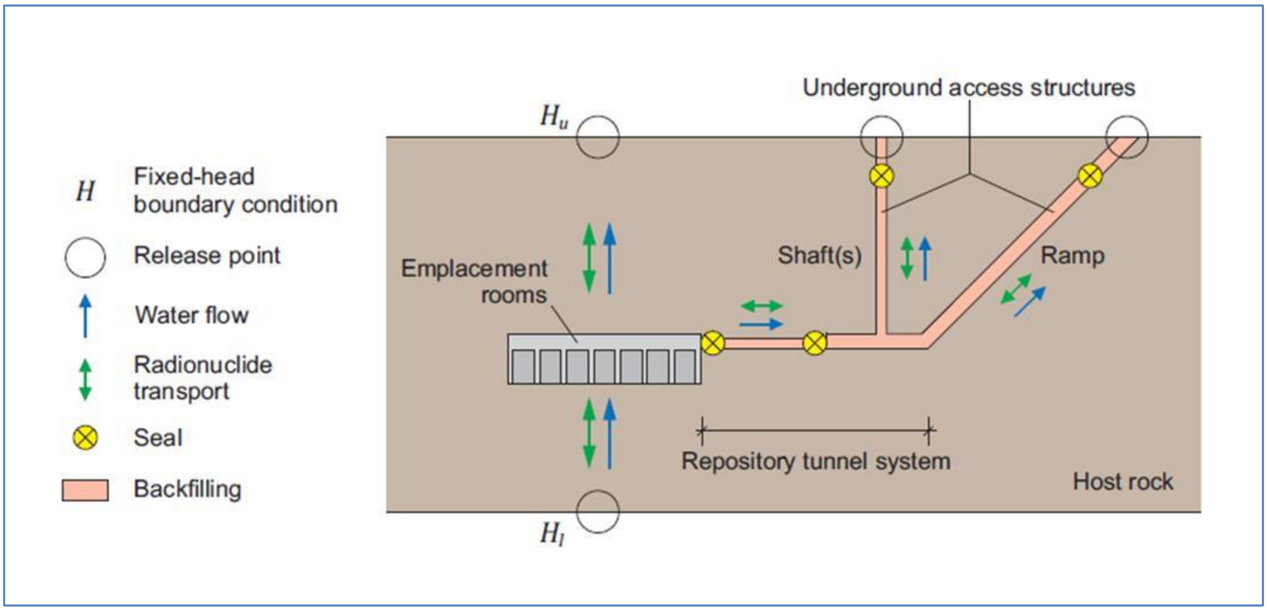

Figure 3-3. Possible access routes considered in modelling for a GDF for HLW and/or L/ILW in clay in Switzerland (Poller et al. 2014).

3.3 Scenario uncertainty

Some TSPAs, particularly those concerned with disposal concepts in low-permeability sedimentary host rock, consider scenarios that explicitly include a situation of poor seal performance. In such scenarios, however, advective migration of radionuclides generally remains limited, because virtually no water enters the disposal areas owing to the low hydraulic conductivity of the host rock (e.g. ONDRAF/NIRAS 2001, NWMO 2011). The bounding case of abandonment of a GDF before closure, i.e. before emplacement of final tunnel closures and shaft/access ramp seals, is included in a number of TSPAs (e.g. Andra 2005b). In the case of the Swedish TSPA for disposal of spent fuel in a crystalline host rock, the abandonment calculation is considered as a Future Human Action scenario (SKB 2015).

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Full-Scale Tunnel and Shaft Seals: Tunnel Sealing Experiment (TSX) and Enhanced Sealing Project (ESP) at Canadian Underground Research Laboratory (URL)

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Full-scale shaft and tunnel sealing installations were constructed at Canadian Nuclear Laboratories (CNL), Underground Research Laboratory (URL) as part of multinational co-operative research projects. The Tunnel Sealing Experiment (TSX) consisted of full-scale concrete plug and a bentonite-based bulkhead installations, both keyed into the tunnel. The region between these two components was sand-filled, flooded and hydraulically pressurized to 4.2 MPa and then heated to 85°C. The effects of hydraulic pressure and temperature on seal performance and the surrounding rock were monitored, allowing evaluation of the system's Thermal-Hydraulic-Mechanical-Chemical (T-H-M-C) evolution. Both components provided effective hydraulic barriers. In 2009 the Enhanced Sealing Project (ESP), a plug consisting of concrete and in situ compacted bentonite was installed at a depth of ~ 275m in a drill and blast excavated shaft. The Thermal-Hydraulic-Mechanical (T-H-M) conditions have been to determine the interactions between the Fracture Zone (FZ), the seal and the Excavation Damaged Zone (EDZ) adjacent to it. It has also provided valuable information regarding the nature of hydraulic interactions vertically across a low-permeability seal. A second seal constructed using precompacted bentonite blocks was installed in a bored shaft to complete the isolation of the lower sections of the URL.

The TSX and the ESP have provided valuable information regarding construction of full-scale tunnel and shaft seals that effectively restricted water movement past them in a repository-type environment. They have also provided valuable field data, against which numerical simulations can be tested, improving confidence in numerical predictions related to post-closure system evolution.

1. Background

Canadian Nuclear Laboratories (formerly Atomic Energy of Canada), operated an Underground Research Laboratory (URL) in a granitic pluton within the Canadian Shield since 1980. In 2007 decommissioning of the facility was initiated and the surface facility removed in 2014. During the URL's operation, the URL was host to numerous repository sealing investigations in various-scale experiments. Two of the large-scale experiments were the Tunnel Sealing Experiment (TSX) in 1997-2007 and the post-closure Enhanced Sealing Experiment (ESP) 2009-2016 (ongoing).

The TSX was an internationally-funded project involving WIPP (USA), Andra (France) and JNC (Japan). It consisted of two independently constructed and monitored components: a 3.5 m-long un-reinforced concrete plug and a ~2.6 m long bentonite-based bulkhead, both keyed into the tunnel (Fig. 1). Located in a tunnel excavated in the highly stressed rock at the 420 Level of the URL the region between these structures was sand-filled, flooded, pressurized to 4.2 MPa and heated to 85°C and the effects of hydraulic pressure and temperature being monitored.

The ESP is an international collaboration Research Development and Demonstration Project that has been funded by Andra (France), CNL (Canada), NWMO (Canada), Posiva (Finland) and SKB

(Sweden) at various times during the period 2009-2016. Two shaft plugs, spanning a water-bearing fracture (FZ-2), were installed at a depth of approximately 275m below ground surface as part of closure of the URL. The first plug was installed in a drill and blast excavated access shaft and the second in a raise-bore ventilation raise. These composite plugs consist of a 3m-long densely compacted bentonite-sand component sandwiched between two 3m-long concrete segments (Fig. 2) in the 4.8m diameter shaft. In the beginning of the experiment, the URL was artificially flooded to within 1 m of the shaft seal's base. As the region above the plugs has naturally flooded, the thermal-hydraulic-mechanical evolution of the plug located in the access shaft has been monitored. Since the access shaft and ventilation raise are connected at 240 and 420 level, if either plug failed, the response would be seen in the sensors monitoring the main shaft plug.

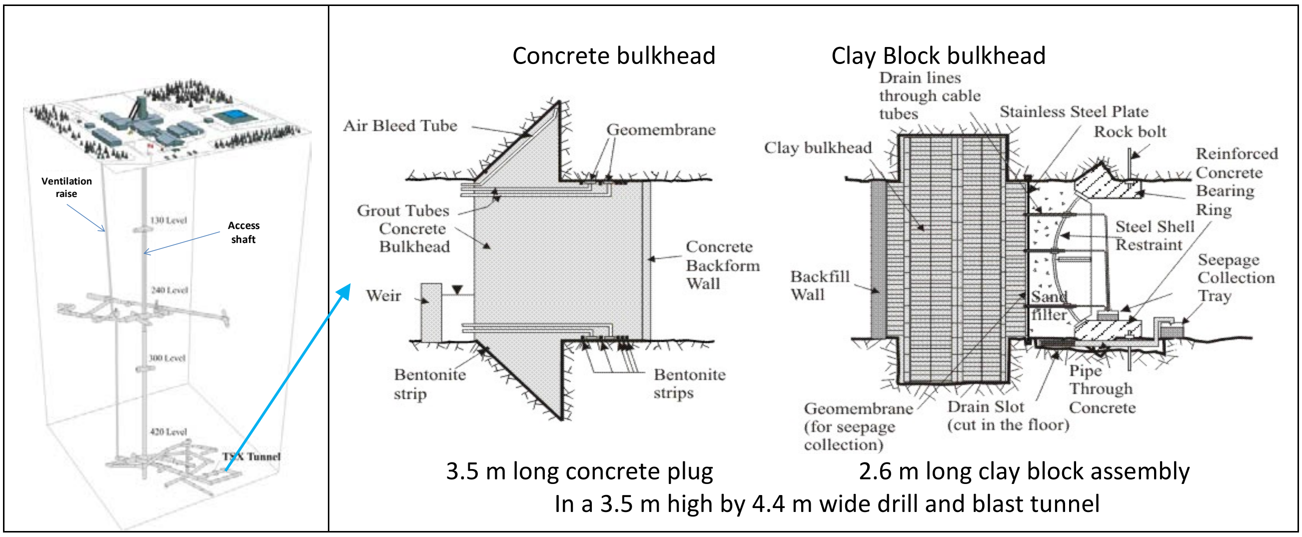


Fig. 1. Tunnel Sealing Experiment (TSX) at -420 m Level of URL (Martino et al. 2008)

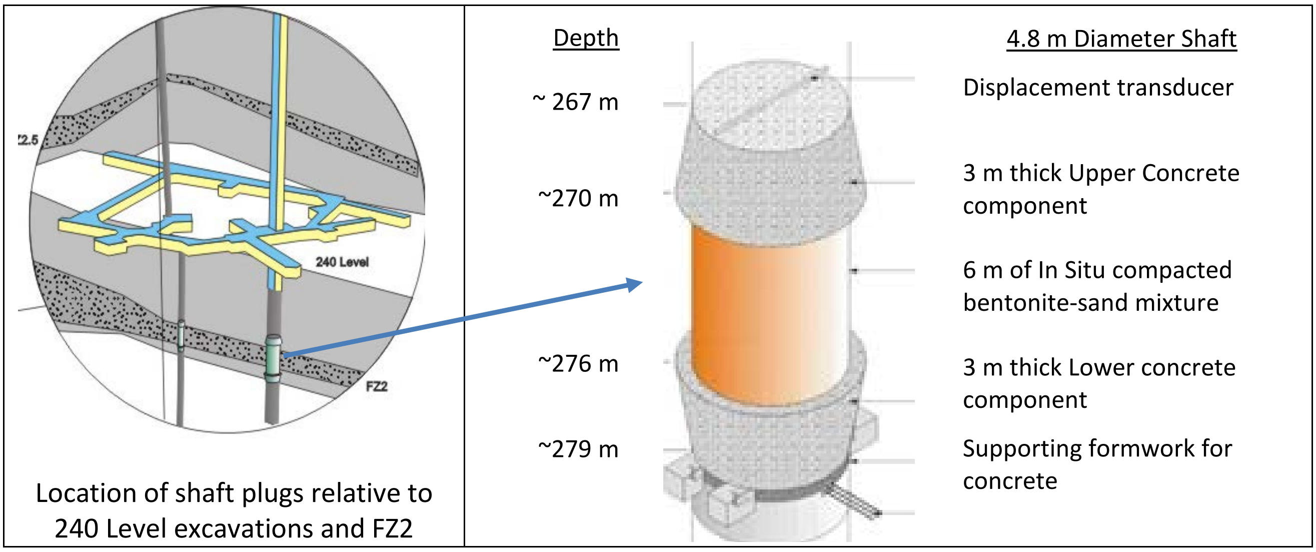


Fig. 2. Enhanced Sealing Experiment (ESP) (Dixon et al. 2012)

2. Scope, Objectives and Methods

Both the TSX and ESP were designed with the intent of demonstrating the constructability of full-scale sealing systems for isolation of tunnels and shafts of the types that would be encountered in a repository for nuclear fuel waste. Beyond basic demonstration of construction, these installations were intended to provide information on the evolution (thermal, hydraulic, mechanical, and chemical) of plugs installed in a deep geologic environment. This was accomplished through construction of these structures using conventional technologies (block and in situ compacted bentonite-based sealing materials and low-heat, high-performance concretes). Associated with each installation, was an extensive monitoring system that tracked the evolution of the clay, concrete and adjacent rock mass. In both projects the plugs for the TSX and ESP were monitored for periods of 10 and 7+ (ongoing) years, respectively. Ultimately the information gained provides field data for use in developing numerical models to predict their T-H-M and Chemical evolution.

3. Methods

The TSX and ESP required use of sensors that were physically modified to ensure their survival under the harsh T-H-M conditions present. These installations also allowed various sensors and sensor technologies to be evaluated for their potential use in repository-type environments.

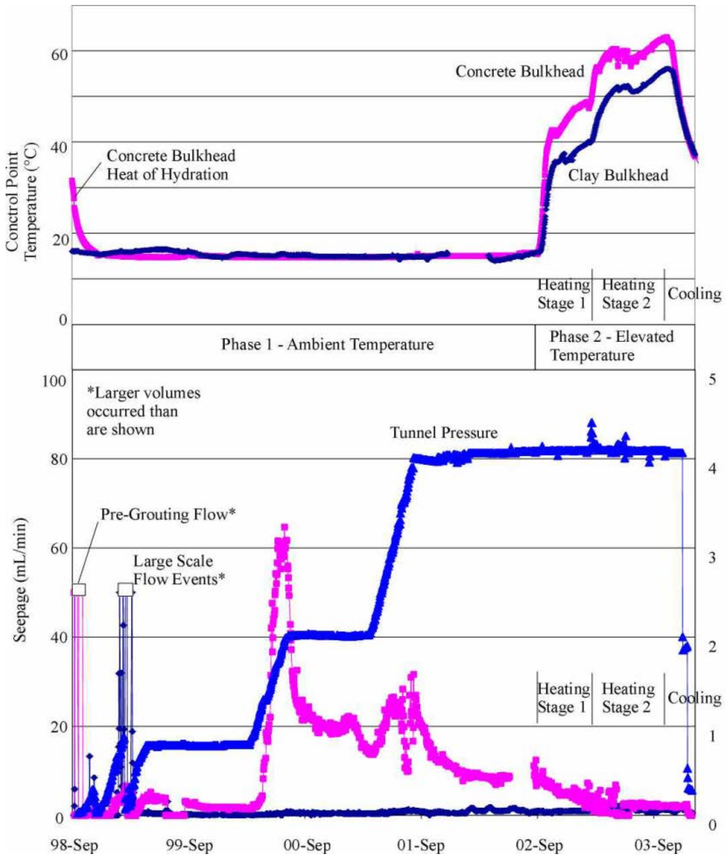
The TSX required monitoring of: temperature of the seals, the development and transfer of hydraulic and mechanical pressures within the seals, at their interface with the surrounding rock mass and within the adjacent rock. Additionally, water uptake by the initially unsaturated bentonite sealing materials needed to be tracked. Sensors used in the collection of these data included: psychrometers and TDR's for water uptake monitoring, vibrating-wire total and hydraulic pressure sensors, fiber-optic strain sensors (for concrete shrinkage) and thermocouples for temperature monitoring. Additionally an extensive seepage monitoring and collection system was installed at the downstream face of each bulkhead. The geosphere in the vicinity was also monitored for generation of microfractures and an excavation disturbed zone through use of micro-seismic and acoustic emission monitoring systems. In total 928 sensors (including 365 temperature sensors), were installed in the TSX (Martino et al. 2008).

The ESP is a less intensively instrumented installation requiring monitoring via sensors capable of providing output to distantly located dataloggers (~275m up a flooding vertical shaft Dixon et al. 2012). This constrained the usable technologies. The ESP was instrumented to monitor the same types of parameters as the TSX: temperature, hydraulic and mechanical pressures as well as water uptake by the clay. Moisture sensing technologies included psychrometers and TDRs. Total and hydraulic pressures were monitored using both fibre-optic and vibrating wire sensors. Fibre-optic sensors were used to monitor concrete strain during curing and a variety of thermal couple and thermistors were used to monitor temperature changes. In total, 100 sensors were installed in the ESP, of which 36 were intended to track longer term (>4 years) H-M evolution. The closure and demolition in 2014 of the surface facilities at the URL meant that the system needed to transition from a fully automated indoor location to an unserviced, stand-alone facility.

4. Results and Discussion

4.1 TSX

Monitoring of the TSX was primarily focussed on evaluating the effectiveness of the two bulkhead components in restricting water flow. The influences of hydraulic head and temperature on the flow were determined as well as the saturation process associated with the clay bulkhead (Fig. 3). The chamber between the two bulkheads was successfully pressurized to 4.2 MPa and heated to 85°C, although the concrete and clay bulkheads only achieved approximately 62°C and 55°C, respectively, during the time the TSX was operated. The concrete bulkhead, although composed of low-heat, low-pH, low-shrinkage, high-performance concrete exhibited sufficient localized shrinkage to generate preferential water flow paths at several locations along the concrete-rock interface. This required post-grouting to be undertaken, an activity that was planned for in experiment design through the installation of several grouting rings at the time of bulkhead construction. Grouting successfully reduced the seepage past the concrete from >0.05 L/min to <0.002 L/min at ~800 kPa hydraulic pressure in the central chamber. The concrete bulkhead showed several notable changes in flow past it over the course of time after grouting with seepage reaching ~0.065 L/min approximately 2 years after grouting. With time (2 more years), seepage decreased to ~0.01 L/min, even as the hydraulic pressure was increased to 4.2 MPa, likely as the results of bentonite fines from the pressure chamber fill entering and clogging the flow paths. When the system began to be heated, seepage decreased further, reaching approximately 0.003 L/min under a 4.2 MPa hydraulic head at the time of test termination.



Main Observations:

Concrete Bulkhead
-Post-grouting of concrete reduced seepage from >0.05 to <0.004 L/min @800 kPa.
-Seepage past concrete decreased with time.
-Heating resulted in further reduction in seepage.
-End-of-Test seepage rate was ~0.003 L/min at 4.2 MPa hydraulic head

Clay Bulkhead
-Early stage hydration exhibited several large flow events but no discernible erosion of clay.
-Flow was largely limited to block interfaces (during initial hydration period) and the rock-clay interface once near-saturation was achieved.
-Once initial clay hydration was achieved seepage was extremely low, <0.002 L/min.

Rock
-Rock around TSX was stable while installation was pressurized and bulkheads present.
-Post-test saw re-activation of stress-induced rock damaging processes.

Fig. 3. Evolution of temperature and seepage past TSX bulkheads (Martino et al. 2008)

4.2 ESP

Monitoring of the ESP is an ongoing activity as of 2016. The main shaft seal is very gradually taking on water and approaching saturation. The moisture sensors installed in the clay near the rock-clay and concrete-clay interfaces showed rapid saturation while the core of the main shaft seal has shown more gradual wetting (Fig. 4), as water moves slowly through the saturated perimeter clay.

The ESP is being done at ambient temperature (~11°C) and saw only a brief thermal disturbance as concrete curing occurred. In the initial phase of the ESP, rapid pressurization of the region below the seal and gradual pressure increase in the region above it. It was anticipated and observed, that even though the concrete used was low shrinkage, there would be open interfaces between the rock and concrete. The concrete components were designed such that their only role was to constrain the clay and prevent it from swelling out of its as-placed location. Steadily increasing hydraulic pressure above the seal is being observed as the shafts continue to flood (Fig. 5), (Priyanto et al. 2015, 2016). Were there to be an open or easy connection for water movement past the shaft seal then the hydraulic pressures along the length of the shaft would be entirely attributable to the elevation head. This is not what has been observed with a substantial pressure differential developing across the clay component. There was some evidence of partial over-pressure release during 2011-2012 but the pressure across the seal never decreased levels attributable to hydraulic head alone.

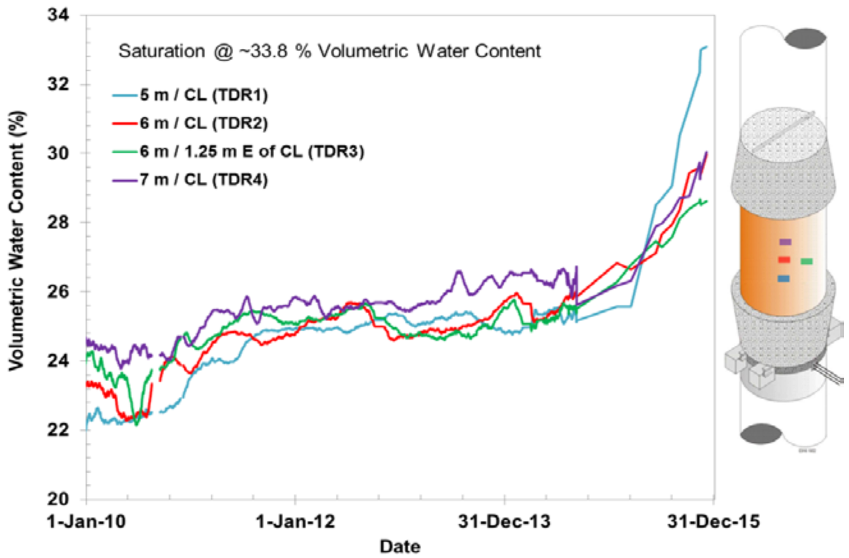


Fig. 4. Water uptake in core of clay plug (TDR data) (Priyanto et al. 2016)

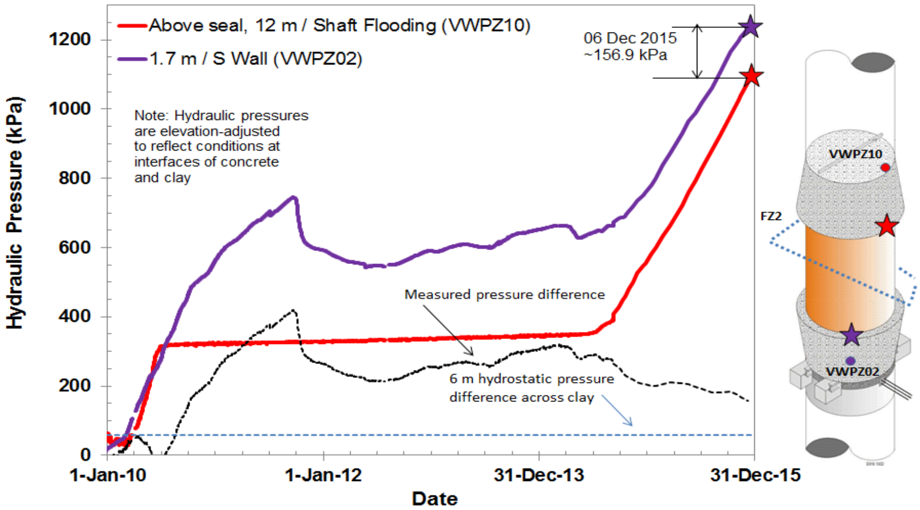


Fig. 5. Hydraulic pressures above and below main shaft plug (Priyanto et al. 2016)

As of mid-2014, the large horizontal developments at the 240 Level of the URL were completely flooded and water began to rise rapidly into the open shafts. This has resulted in substantial ongoing hydraulic pressure increase above and below the plug. Although the hydraulic pressure increases above and below the plug have shown similar rates of increase, a differential between the two regions has been maintained, although it is very gradually decreasing. This is interpreted as indicating that the lower region is only very poorly connected with FZ2 and FZ2 is similarly poorly connected to the open shaft. As there is no direct connection between the upper and lower shaft sections, a pressure difference is observed since excess hydraulic pressure is not able to be relieved quickly enough to eliminate the gradient. This condition may continue to exist for a considerable time if the connection between the open and isolated shaft sections remains poor. If the current flooding rate of ~3000 L/day continues, the upper shafts should flooded after August 2018.

4.3 Numerical Modelling of TSX and ESP

The TSX and ESP have been used in the development of numerical models developed to describe and predict performance and evolution of tunnel and shaft seals, as well as the geosphere immediately surrounding them. Examples of numerical modelling completed using these data are: Guo et al. (2003, 2005, 2006) TSX and Priyanto 2011, Priyanto et al. (2014a, 2014b, 2015) ESP.

5. Conclusions

The TSX and ESP have demonstrated, at full-scale, the ability to construct plugs and seals that can be installed in a deep geological environment where severe spatial constraints and environmental conditions are present. These installations have allowed for monitoring of the evolution of seals and plugs under natural and accelerated water uptake, providing valuable field demonstration data for use in developing and calibrating numerical models that can be used to describe and predict seal evolution. They have also highlighted the importance of field tests as unanticipated processes can complicate prediction of system evolution.

Acknowledgements

The TSX was funded by WIPP (USA), Andra (France) and JNC (Japan). The ESP is currently supported by CNL (Canada), Andra (France) and Posiva (Finland) and past participants are NWMO (Canada), SKB (Sweden). The technical and financial support of these organizations at various points in these projects is gratefully acknowledged.

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The Gas-Permeable Seal Test in the Grimsel Test Site

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Summary

Gases (hydrogen, methane, carbon dioxide) may accumulate in the emplacement caverns of a geological repository for low/intermediate-level waste (L/ILW) due to the corrosion and degradation of the waste. Gas permeable backfill and tunnel seals have been proposed as a viable option to release a part of the gas into the operation and access tunnels while still maintaining low hydraulic conductivity and thereby limiting radionuclide transport.

A large-scale Gas Permeable Seal Test (GAST) has been initiated to demonstrate the effective functioning of a sand-bentonite mixture for gas permeable tunnel seals and to obtain upscaled water and gas permeabilities. The system was designed to realistically simulate the pressures expected in a repository seal at ~500 m depth. The evaluation of material emplacement techniques and diverse QA measurements were further important aspects in the construction phase of the experiment.

This paper presents the GAST design concept and its implementation. The heart of the test is a sand/bentonite element (8 m long, 3.0 m diameter) with a total volume of ~46 m^3. Granular bentonite surrounds this element to protect the instrumentation system and prevent water and gas by-passes along the interface to the host rock. Monitoring sensors in the sand/bentonite element and in the granular bentonite provide information on total pressures, pore pressures, relative humidity and water content.

1 Introduction

Opalinus Clay has been proposed as the preferred host rock for a deep geological repository for low and intermediate-level waste (L/ILW) in Switzerland (Nagra, 2014a). Opalinus Clay is characterized by a low permeability and is, therefore, an excellent barrier against radionuclide transport. Gas migration in a L/ILW repository is a critical component within the safety assessment of proposed deep repositories in low-permeability formations. In L/ILW repositories, anaerobic corrosion of metals and degradation of organic materials produce mainly hydrogen and methane. The generation, accumulation, and release of these gases from the disposal system may affect a number of processes that influence the long-term radiological safety of the repository (Nagra, 2008; Nagra, 2014b).

With the concept of the "engineered gas transport system" (EGTS), a backfill and sealing system was developed that allows the controlled transport of gases along the access structures without compromising the radionuclide retention capacity of the engineered barrier system (Nagra, 2008). The generic layout of the L/ILW repository is show in Figure 1-1. High-porosity cementitious mortar is used to fill the void spaces within the emplacement caverns. After backfilling of a cavern, it is closed with a gas-permeable seal. Other underground structures in the host rock are backfilled with sand/bentonite or with processed excavated Opalinus Clay. A gas-permeable seal separates the underground structures in the host rock from the backfilled ramp and contact with the overlying confining rock units. Access or ventilation shafts involve vertical repository seals.

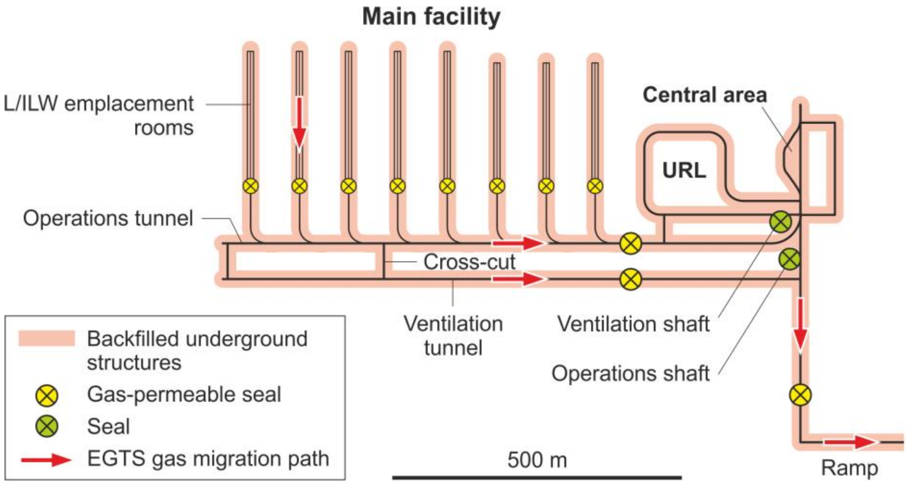

Figure 1-1. Nagra's generic concept for an L/ILW repository, planned backfilling and position of seals. EGTS gas migration path is shown by red arrows. (after Poller, 2014).

The backfill material foreseen for the EGTS is a mixture of sand and bentonite. Sand/bentonite (S/B) mixtures have a significantly lower gas entry pressure than pure compacted bentonite of equivalent water permeability, and the sand content allows the gas permeability to be adjusted to a desired value. The use of bentonite in the mixture further ensures good sorption for many radionuclides, self-sealing and a low hydraulic conductivity and thus ensures the required barrier functionalities (Dixon et al., 2002; JAEA, 1999; Mata Mena, 2002).

To demonstrate the effective functioning of gas permeable tunnel seals, the large-scale gas permeable seal test (GAST) has been developed. This paper presents the scope of the test, its construction in the Grimsel Test Site (GTS) and outlines the quality assurance program.

2 Project scope and requirements

GAST focuses on the behaviour of a gas permeable seal under realistic boundary conditions and features a large scale in situ experiment. The main aims of the in situ experiment are to (1) demonstrate the effective functioning of gas permeable seals at a realistic scale and pore pressure; and (2) determine up-scaled gas and water permeabilities of S/B seals (i.e. two-phase flow parameters for large-scale models). For GAST water and gas injection pressures up to 5 MPa were considered as design values to approximate the expected hydrostatic pressures in a repository seal at ~500 m depth. Secondary objectives include the evaluation of emplacement techniques and necessary methods for quality assurance (QA).
The requirement for the S/B seal of the GAST project was to obtain an intrinsic hydraulic permeability of 10^{-18} m^2. The test design encompassed the use of natural sodium Wyoming bentonite (MX80) and a high degree of homogeneity in the emplaced S/B mixture. Laboratory tests (Senger et al., 2006; Tashiro et al., 1998) indicated that mixtures of 80% sand, 20% bentonite combine the required low water permeability with enhanced gas permeability. Recent laboratory tests at the École polytechnique fédérale de Lausanne (Manca, 2015) for samples compacted at 1.5 and 1.8 Mg/m^3 were fitted with a van Genuchten model and confirmed gas entry pressures varying

between 10 and 360 kPa dependent on dry density wetting/drying curve and the suction range over which the model was fitted. A second series of permeability tests showed that emplacement dry densities of 1.6-1.65 Mg/m^3 are necessary to achieve an intrinsic S/B permeability of 10^{-18} m^2. Finally an average dry density of 1.7 Mg/m^3 was chosen as target value, and a minimum of 1.6 Mg/m^3 was considered acceptable at locations where compaction was difficult. Proctor tests indicated an optimum water content for the S/B mixtures between 10-13%.

3 Implementation

3.1 Pre-testing

In order to evaluate and optimize emplacement methods that meet above requirements, field pre-tests were carried out. It was found that sand and bentonite need to be mixed in a concrete mixer drum with a vertical rotating axis (Teodori et al., 2013). For logistical reasons the S/B mixtures were prepared and packed in big bags before delivery to the GTS and in situ emplacement. Compaction tests showed that electrical backfill rammers (Wacker) and compacting plates reach the target emplacement dry density of 1.7 Mg/m^3 if an initial horizontal layer of 19 cm loose mixture is compacted. The compacted layers reached an effective final thickness of about 10 cm.

3.2 Test design and emplacement

The GAST experiment is located at the end of a 3.5 m diameter tunnel in the GTS ~400 m below surface. The hydraulic conductivity of the excavation damage zone in the vicinity of the tunnel – it had been excavated by a tunnel boring machine – is believed to be in the same range or lower than that of the seal and is therefore disregarded. The very few geological structures found in this part of the tunnel were sealed with two-component resin and impermeable mats to ensure a tight and stiff boundary against the expected injection pressures.
The hart of the test consists of 28 horizontal layers of in situ compacted S/B (Figure 3-1) with a length of 8 m and a target dry density of 1.7 Mg/m^3. The radial rock/seal interfaces were filled with a 25 cm thick section of granular bentonite material to obtain a tight confinement against the surrounding host rock and minimize preferential water or gas flow paths along the interfaces. Granular bentonite was also used to backfill the headspace above the seal, where insufficient space made the vibrators unsuitable. Vertical gravel filters were emplaced at both ends for controlled water and gas injections. Material volumes and bulk parameters are summarised in Table 3-1. Two walls, made of compacted bentonite blocks and granular bentonite, constitute the watertight seals at the tunnel end and at the confining concrete bulkhead. On-site construction started in 24th October 2011 and was completed on 16th May 2012.

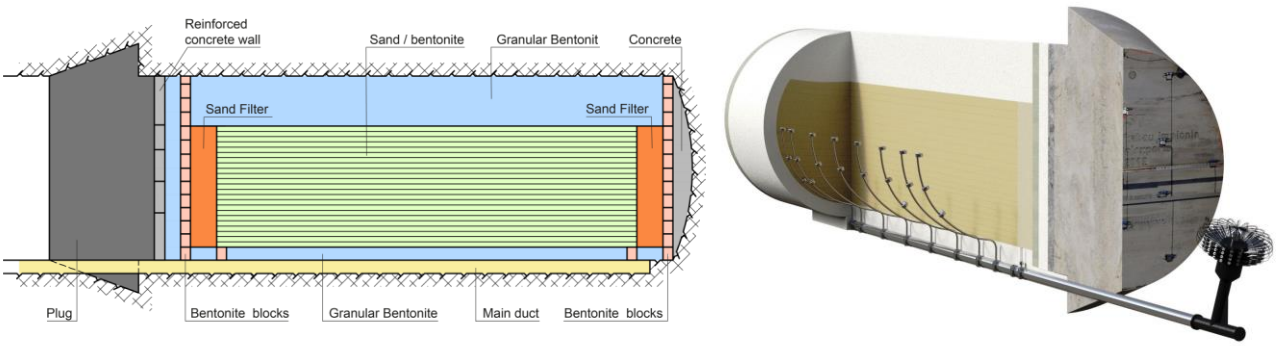

Figure 3-1. Conceptual experimental layout (left) and cut-away visualization (right) showing sand/bentonite and granular bentonite bodies with instrument risers and main duct below the tunnel.

Table 3.1. Bulk parameter of emplaced materials.

Element		S/B	GBM	Sand
Material		80/20 sand / bentonite	Granular bentonite	Quartz sand
Total volumes	[m^3]	46	~36	2×3
Average dry density	[Mg/m^3]	1.65	1.45	not measured
Target permeabilities	[m^2]	1.00E-18	<1E-18	1.00E-15

3.3 Instrumentation

The GAST experiment is equipped with multiple sensors to monitor the sealing behaviour during saturation phase and gas transport in the subsequent gas injection phase as well as the hydraulic effects on the host rock and concrete bulkhead. The expected injection pressures of 5 MPa set the constraints for instrumentation design. A variety of sensors (Figure 3-2) are placed at the rock and bulkhead walls (total pressure), at the top of selected S/B layers (piezometers) and in the granular bentonite head space (relative humidity). Upper and lower filter sections are equipped with hydraulic steel tubes (port lines) used for water and later gas injections. The interface between filter and S/B at the bulkhead side (see Figure 3-1) is equipped with elongated ribbon TDR sensors (TDL) with capability to localise saturation changes along the sensor.

Two cable ducts feed all cables from the sensors in granular bentonite through the upper part of the concrete bulkhead. Cables and lines from the sensors within the S/B seal are routed in steel tubes to the risers and then to the main duct that runs below the seal as shown in Figure 3-1. Initially the main duct cable outlet was open. After a leakage event with water outflow through the main duct it had to be closed with a well head featuring individual cable feedthroughs. The well head is shown to the right in Figure 3-1.

SENSOR	Abbreviation	Quantity	Symbol
Pore pressures	PPE	39	● (red)
Port lines	PL	10	■ (red)
Total pressure cells	TPW/TPB	23	○ (green)
Volumetric water content	TDP/TDL	38	● / ▬
Seismic sensor	SE	34	● (orange)
Psychrometers	PS	30	▲ (green)
Relative humidity	RH	20	▲ (red)
Temperature	PT1000	3	
Displacement	DI	4	

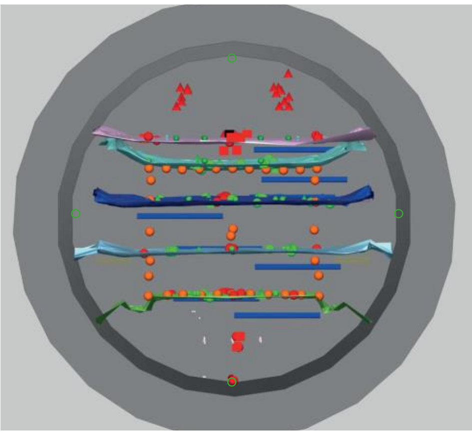

Figure 3-2. List of installed sensors, abbreviations, quantity and symbol (left). Cross-section (right) shows position of the sensors and surfaces of instrumentation layers 40-50 cm apart.

3.4 QA procedures

Mass balance observations just after emplacement assured that the required emplacement dry density was met (Teodori et al., 2013). Dry densities were computed for each completed S/B layer using layer thicknesses from approximately 1 m spaced layer surface coordinates and water content corrected weights of emplaced mixture. An alternative mass balance approach was assessed additionally by performing 3D laser scans typically after four or five layers had been emplaced

(Figure 3-1). The dry densities obtained by these methods ranged between 1.6 and 1.73 Mg/m^3 with an average of 1.65 Mg/m^3 for the complete S/B volume. The third QA method employed direct sampling with a ring cutter (sampling volume ~50 cm^3) at ~1 m spacing, oven drying and on site weighing of the recovered material. Variogram models were derived from this data for density visualisation. The cut-out views in Figure 3-3 exhibit contiguous areas where dry densities range around or above the target value. Local high and low dry densities are highlighted by plotting only values below or above the target value (Figure 3-3 left and right, respectively).

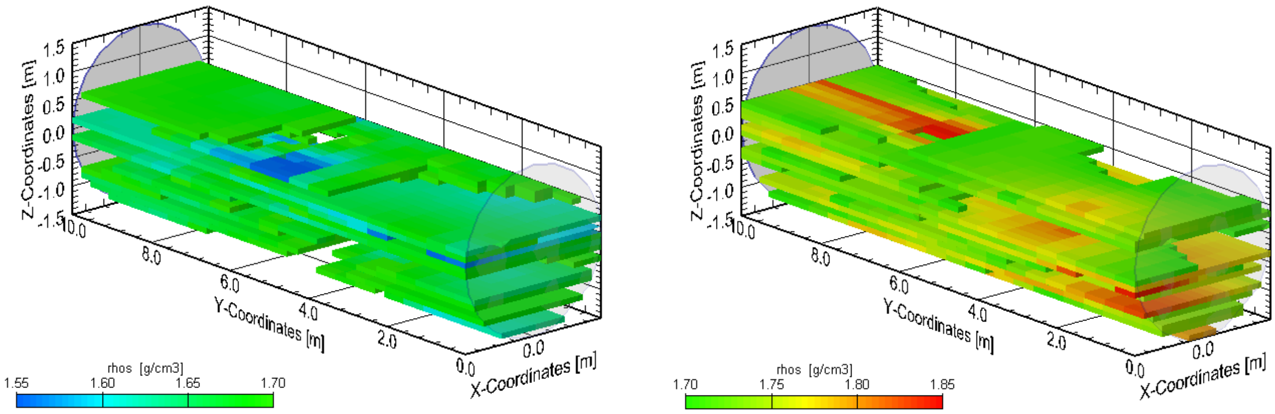

Figure 3-3. Distribution of S/B dry densities smaller (left) and larger (right) than 1.7 Mg/m^3.

3.5 Saturation

Since July 2012 the system is being artificially saturated by water injections into the front gravel filter element. The filter volume was quickly filled but the main bodies of S/B and granular bentonite are slow to saturate. A water leakage that occurred in January 2014 at an injection pressure of about 1.7 MPa interrupted the artificial saturation process. Saturation has been resumed after the necessary remediation works were successfully completed in August 2015. Recent index tests indicated that large volumes of the S/B body are nearly saturated. The upper layers of the S/B and the granular bentonite above it are still partially saturated.

4 Discussion and conclusions

A large scale experiment has been developed and implemented to demonstrate the functioning of gas permeable tunnel seals using in situ compacted sand/bentonite mixtures. Emplacement, compaction and QA measurements for the test body proofed to work very well under field conditions. The overall S/B dry densities showed to be within the range of 1.65-1.73 Mg/m^3, which compares well with the targeted intrinsic permeability of 10^{-18} m^2.

The saturation process – artificial water injections into one of the two gravel filter elements - was interrupted by a leakage event and necessary remediation works. Saturation has recently been resumed and the system is validated for the planned high-pressure injections. In parallel, numerical two-phase flow models are being developed in order to further develop predictive capabilities for future water and gas injection tests.

5 Acknowledgements

The authors would like to thank the GAST field team members from Aitemin, Solexperts and Versuchsstollen Hagerbach. Dave McKie and Bruno Kunz (Nagra) are thanked for preparation of the visualizations in some the figures.

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Experiences from an In-Situ Test Site for a Sealing Element in Shafts and Vertical Excavations in Rock Salt

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The repository for radioactive waste at Morsleben (ERAM) in Germany containing low-level and medium-level wastes is under licensing for decommissioning. The decommissioning concept includes the sealing of the two shafts and one vertical seal. These seals consist of sealing elements containing gravel and bitumen and/or asphalt. Both components, gravel and bitumen, have been tried and tested as single elements in the closing of shafts. A combination of both elements is used for the first time. Therefore, several tests have to be carried out. After laboratory and large-scale tests at the surface, an in-situ test underground as an experimental set-up comparable to the future sealing elements has been performed.

The test has been carried out in a vertical excavation with a nearly square base area of about 12 m^2. The height of the sealing element built of gravel and asphalt is about 6 m. The filling success is assessed by the measured pressure and by calculating the remaining pore volume between gravel grains and bitumen based on the masses of the materials used and the measured volume of the excavation. To assess the influence of hot bitumen on the rock mass, temperature measurements are carried out.

This paper gives an overview of the results from the surveying measurements and focuses on the construction process taking into account the difficulties of working underground but meeting the quality requirements of a long-term sealing structure.

1 Introduction

The radioactive waste repository Morsleben (ERAM) serves as a repository for low and intermediate level radioactive waste. It is located in Saxony-Anhalt, Germany. Currently, the repository is in the phase of decommissioning. The shafts Bartensleben and Marie were excavated at the beginning of the last century and are connected on the 1st and 3rd level. Due to the former mining for the production of potash and rock salt, the excavation ratio is very high.

Overall, in the period from 1971-1991 and from 1994-1998, 37.000 m³ of radioactive waste were emplaced. The storage areas are in the mine Bartensleben in the northern, eastern, southern and western fields and also, to a smaller extent, in the central part (Fig. 1).

The decommissioning concept consists of an extensive backfilling of cavities, drifts and sealing of the two shafts. Additionally, one vertical and several horizontal sealing elements to separate the emplacement areas from the other mine areas will be built. All these sealing structures will constrain possible infiltration of brine and the migration of radionuclides into the biosphere.

The shafts will be sealed with a combination of various sealing elements consisting of gravel, asphalt and/or bitumen and clay. The sealing concept using gravel and asphalt and/or bitumen will also be used in one vertical excavation that connects several horizontal drifts /1/2/.

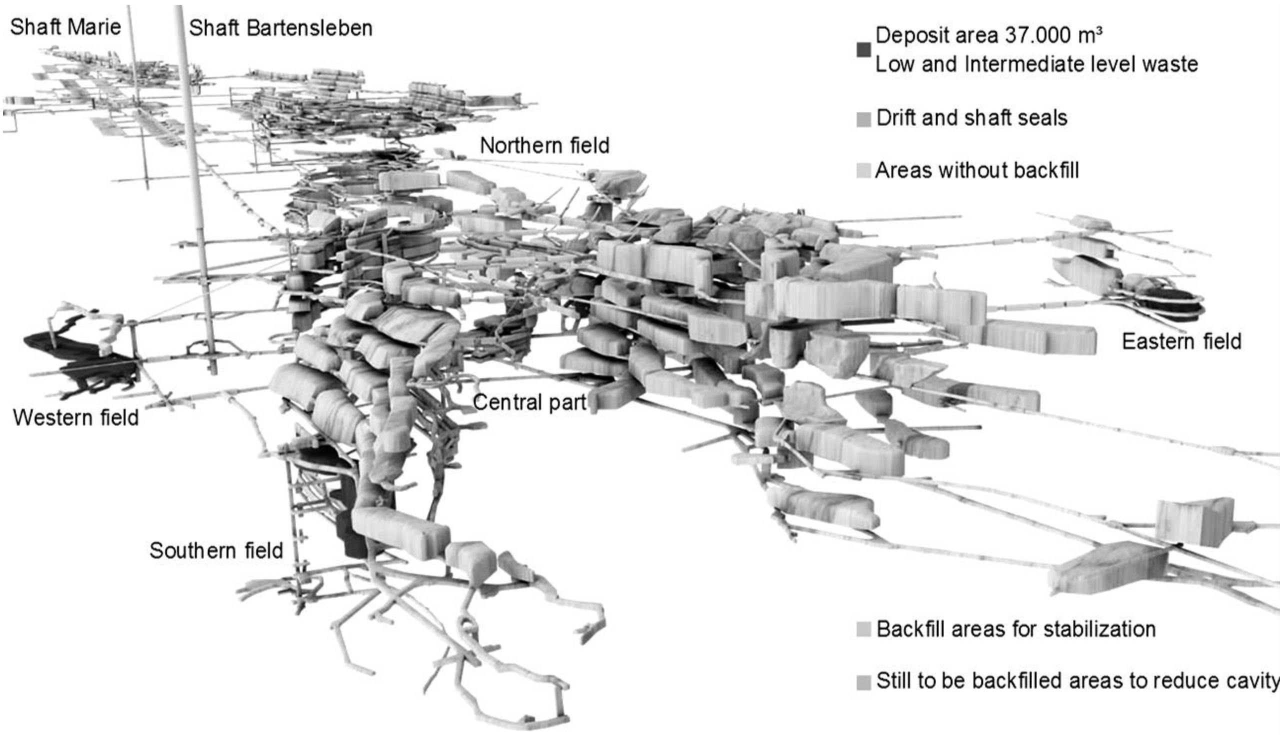

Fig. 1: Mine fields of Bartensleben with deposit areas (in foreground) and Marie (in background)

To show that these sealing elements can be constructed with the quality assumed in the safety assessments, several tests have been carried out. To demonstrate the material features and functionality of the combined abutment/sealing elements of gravel and bitumen and/or asphalt set out in the plans, several trials were executed.

In 2013, BfS tested the pouring of asphalt in gravel layers in a large-scale test at the surface. Based on monitoring data, the individual pouring tests were analyzed and their success was evaluated /3/-/6/. This way, important experiences could be gained for the large-scale test underground. In 2015, an in-situ test as an experimental set-up comparable to the future sealing elements was performed.

2 Scope and Objectives

Starting from the concept and the assumption in the safety assessments for the future sealing elements, a test site was chosen at the ERAM. The main goal was to show the technical feasibility of building a plug consisting of gravel and asphalt related to the logistic constraints underground as well as to the health and safety aspects concerning working with about 190°C hot asphalt in a vertical excavation.

Additionally, the influence of the hot asphalt on the surrounding rock salt and the pressure resulting from the asphalt filling the pores between the grains of the gravel are measured. A principle sketch of the test set-up and the measurement system can be found in Fig. 2.

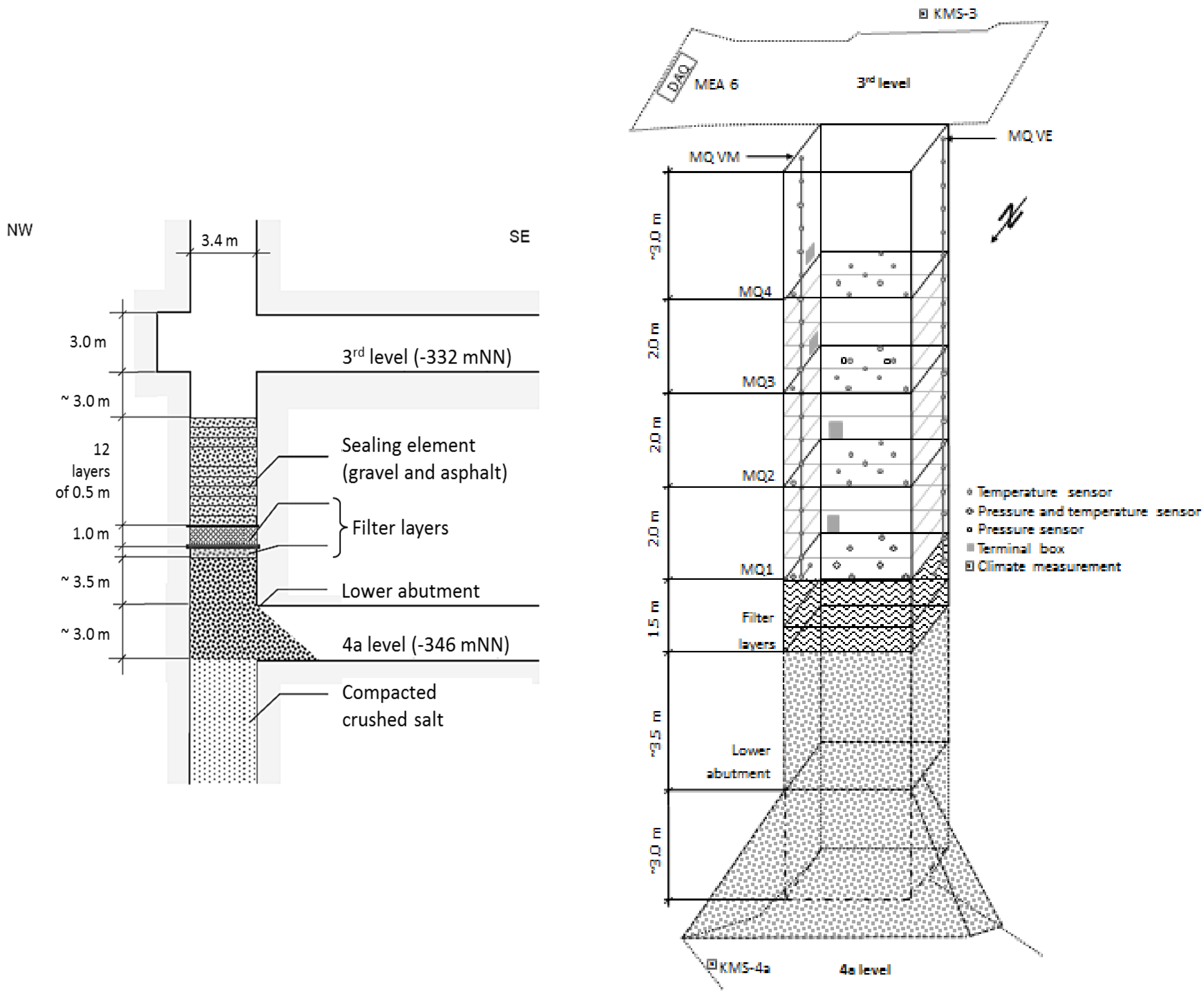

Fig. 2: Principle sketch of the test set-up and measurement system

3 Construction process

The test was carried out in a vertical excavation, the so-called IB blind shaft, with a nearly square base area of about 12 m^2. Among others, the construction site set-up included the following activities:

- The removal of existing equipment in the IB blind shaft,
- The installation of winches for person and material transportation required for the construction of the structure,
- The facilities mounting of the auxiliary ventilation of the working area,
- Mine survey of the blind shaft and marking of thickness of the gravel layers to be constructed.

After building an abutment of gravel and several filter layers, the sealing element with a total height of about 6 m was built. Above the last filter layer, pressure and temperature measurement instruments have been installed.

Before bringing in the gravel, two measuring chains with approx. 20 temperature sensors each were installed on the surrounding rock in the blind shaft. Furthermore, eight pressure sensors were installed on the filter layer at the bottom of the sealing element.

In the process of constructing the sealing element, further temperature sensors were placed in the gravel bed at a height of 2, 4 and 6 m. At a height of 4 m, two additional pressure sensors were placed. The temperature sensors measure the temperature changes in the gravel/asphalt-layers and on the rock surface. The pressure sensors measure the increasing pressure resulting from the filled-in asphalt.

Fig. 3: Transportation of the gravel in the blind shaft

Before starting the construction process, the material properties of the gravel and the asphalt (bitumen with limestone powder as filler) were controlled. Then, building of the sealing element consisted of the following steps: A layer of about 0.5 m gravel was dumped in the excavation and compacted (Fig. 3). The gravel was weighted and the compaction was checked by measuring the volume and calculating the density.

Then, the hot asphalt could be filled in after being weighted as well (Fig. 4). For filling the compacted layer of gravel, the asphalt, which has been produced in an external facility, was heated above ground in an asphalt cooker up to the required temperature of 170 - 190 °C and transported underground.

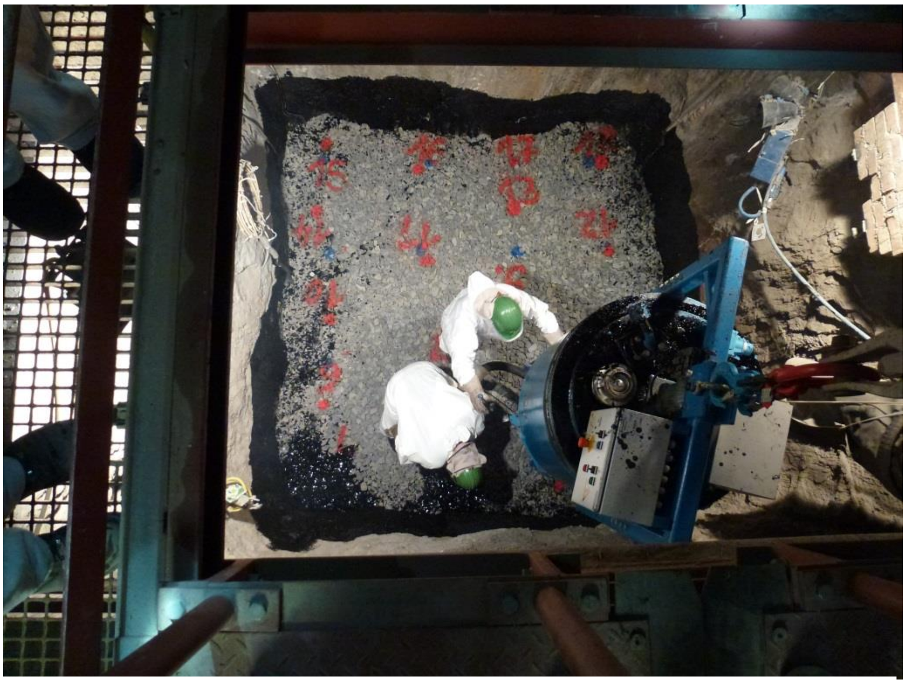

Fig. 4: Filling in the hot asphalt

After different waiting times ranging from about 12 hours to three days after filling, gravel for the next layer was dumped. Following the first layer of approx. 0.5 m thickness, two smaller layers of approx. 0.25 m thickness were built to improve the filling process. Then, 10 layers of approx. 0.5 m thickness were built, up to the planned height of the sealing element of approx. 6 m.

4 Results and Conclusions

The technical feasibility of building a vertical sealing element of gravel and hot asphalt has been shown. All quality requirements were met and all health and safety measures were implemented successfully. To check for potential air pollution during the work with hot asphalt, measurements were carried out by an external institution which stated that the permissible values were not exceeded.

For the temperature influence, see Fig. 5. The temperature in the filled-in asphalt reached about 160 °C just shortly, the temperature at the rock salt reached only about 45 °C at maximum. After some hours, the temperature decreased significantly. The initial surrounding temperature was reached after some weeks.

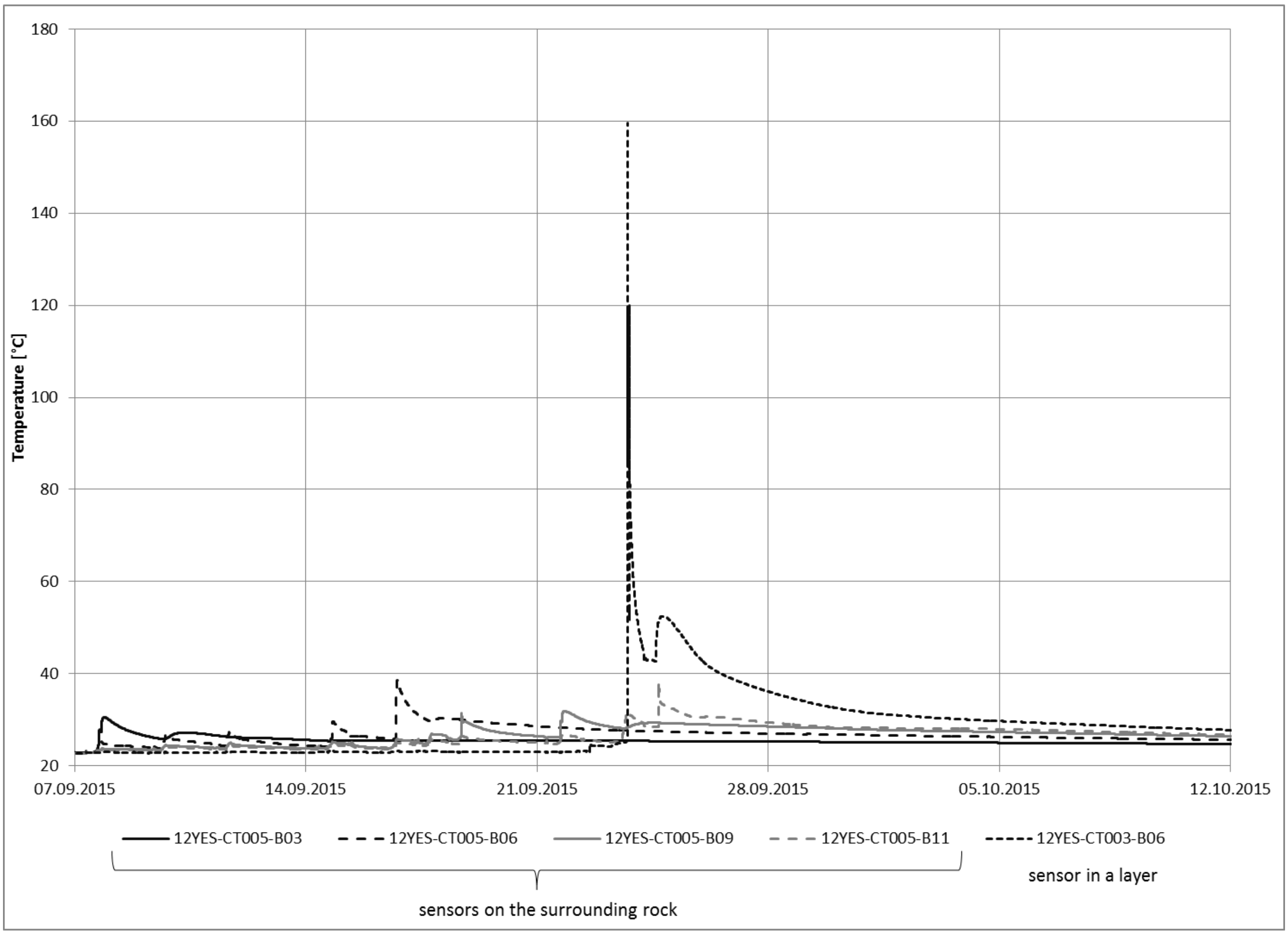

Fig. 5: Temperature in a layer and on the surrounding rock (representative sensors)

The filling success is assessed by the measured pressure, which is plotted in Fig. 6 for the sensors at 4 m height, and by calculating the remaining pore volume between gravel grains and asphalt based on the masses of the materials used and the measured volume of the excavation. For the latter, a remaining pore value of about 1.5% was calculated, which is below the target value of 3%. The pressure measurements prove that the asphalt acts like a liquid.

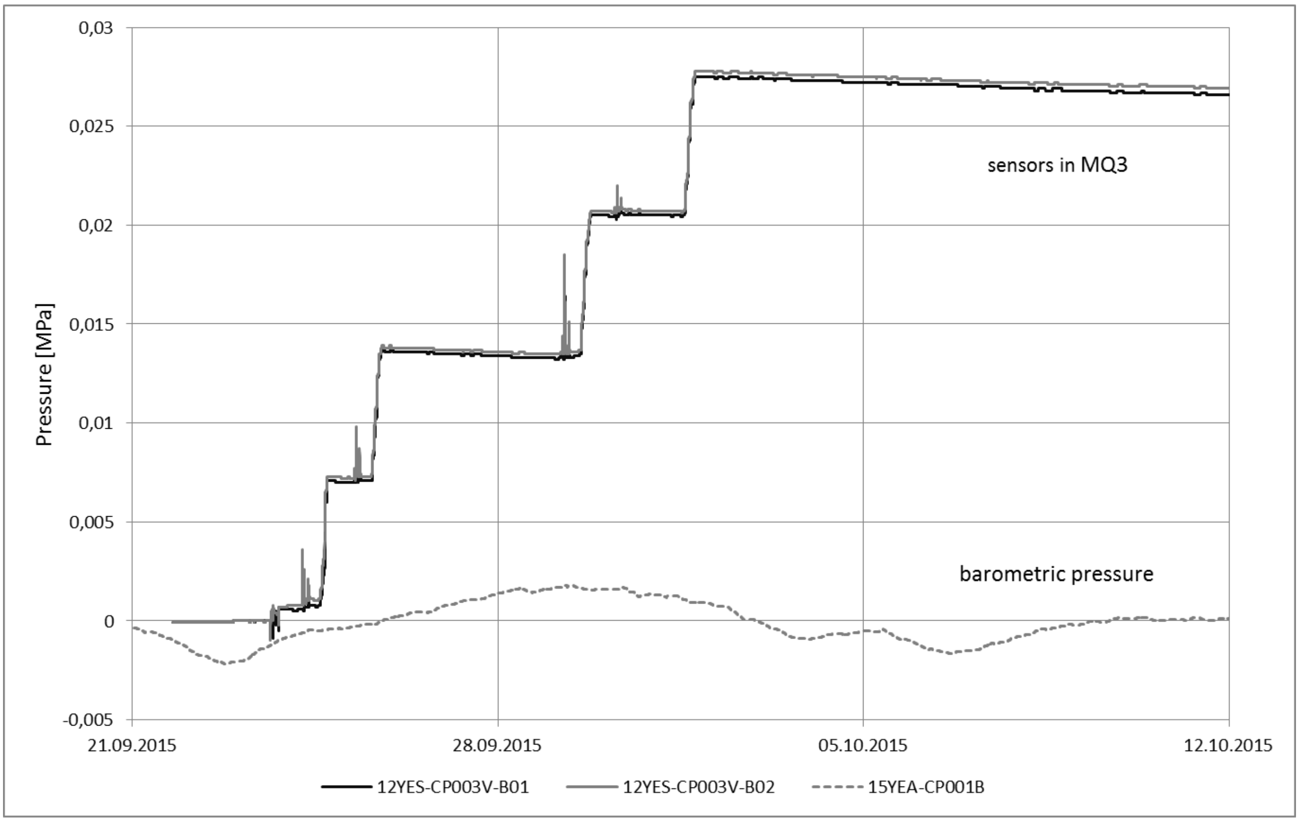

Fig. 6: Pressure at the sensors at 4 m height (MQ3)

The material properties were controlled by sample testing, and the construction process was monitored by quality measurements. The pressure measurements and the calculation of the remaining pore volume document the functionality of the sealing element. After extensive testing, it can be concluded that the vertical sealing elements can be built as assumed.

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Development Of A UK Approach To Sealing Deep Site Investigation Boreholes: Knowledge Transfer From Other Industries

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This paper presents some results from a three year project to develop generic approaches to seal deep boreholes drilled as part of site investigations at a potential Geological Disposal Facility (GDF) site in the UK. The project (Sealing of deep site investigation boreholes: Phase 2) is being funded by Radioactive Waste Management Limited (RWM) and undertaken by a team comprising of Amec Foster Wheeler, Bedrock Geosciences, Clay Technology, Galson Science, Nagra, Quintessa and Schlumberger. We describe how techniques used in the oil and gas industry to place materials in boreholes could be used or modified to seal deep boreholes at a site being investigated to host a potential GDF. The project has previously concluded that post-closure seals in site investigation boreholes associated with a GDF site should be formed from natural materials such as bentonite; therefore, this paper specifically considers the application of oil and gas techniques to place bentonite in deep boreholes.

1 Introduction

At the present time, the UK siting process for a Geological Disposal Facility (GDF) is at the generic stage; no sites are being investigated and there is no preferred geology. In this generic stage, RWM considers three illustrative geological settings in its development of generic disposal concepts [i,ii]. The three illustrative geological settings considered in the 2010 generic Disposal System Safety Case (gDSSC)[1] are higher strength rocks (HSR), lower strength sedimentary rocks (LSSR) and evaporites. In the case of lower strength sedimentary host rocks and evaporite host rocks, the host rock will be overlain by sedimentary cover rocks. In the case of a higher strength host rock, the host rock may either extend to surface or be overlain by sedimentary cover rocks.

2 Scope and objectives

RWM is undertaking R&D into borehole sealing because it expects it will be necessary to demonstrate how site investigation boreholes might be sealed before drilling begins at a potential site. An R&D programme into sealing deep site investigation boreholes commenced in 2013. Phase 1 of the project [iii] comprised of a review of borehole sealing approaches in a range of industries and concluded with a recommended programme of work for a Phase 2 Project. Phase 2 commenced in June 2014 and is scheduled to complete in March 2017. The overall objective of the Phase 2 project is to develop an approach or approaches for sealing deep (up to 2,000m) site

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[1] We recognise that the gDSSC will be updated in 2016 and that the detailed descriptions of the geological environments are currently evolving. For the purposes of this report, we refer to the 2010 gDSSC and supporting documents as published

investigation boreholes against groundwater flow and gas migration in a range of geological settings potentially relevant for a UK GDF. It was the view of the Phase 1 report that generic R&D should be focused on developing and demonstrating sealing concepts for HSR and LSSR environments. The composition of seals in evaporites (using either natural evaporite minerals or salt-saturated cements) would depend on the site evaporite mineralogy, and would be addressed once a site is under consideration.

3 Conclusions from the Phase 1 project

The Phase 1 borehole sealing report [iii] presented the approaches to borehole sealing taken by a number of organisations and industries: overseas Radioactive Waste Management Organisations; oil and gas; CO_2 storage; and, water resources. Borehole diameters and depths of potential relevance to RWM are fairly typical of onshore and shallower offshore oil and gas wells. Likewise, oil and gas drilling encounters many rock types worldwide, from weak overburden, through competent sedimentary formations, to hard basement reservoirs. As such, there is considerable technology and knowledge in the oil and gas industry on borehole sealing that may be appropriate to deep site investigation boreholes for a GDF.

The approach to abandoning/decommissioning boreholes is broadly consistent across the industries considered, although this is sometimes obscured by the different nomenclatures used. The main common themes are:

- sections of boreholes are sealed to prevent or reduce to an acceptable degree the movement of fluids through the borehole for as long as is required. These seals must have sufficiently low permeability and sufficient longevity to meet these requirements. In the Phase 2 ‘Sealing Boreholes’ project, we refer to such seals as ‘post-closure seals’;
- intervals between the seals are filled with materials that provide mechanical stability for the surrounding rock and overlying and underlying seals. Additionally, these materials greatly reduce the permeability of the section relative to that of the open borehole, although this is not their primary function. In the non-nuclear applications that we have reviewed, lengths of cemented casing often remain in-situ between the seals; in this case, the cemented annulus rather than the material filling the casing provides the resistance to flow through the section. We describe the component used to fill the intervals between seals as the ‘support element’;
- seals are placed across lower permeability sections of rock in uncased sections of hole. Their lengths depend on the rock properties and sealing concept; 30m or more is typical. Working in conjunction with the surrounding rock, they restrict fluid movement along the borehole. Seals are not placed directly across high permeability horizons.

4 Conclusions and achievements from the first year of the Phase 2 project

The main conclusions and achievements from the first year of the Phase 2 ‘Sealing Boreholes’ project are listed below.

- The performance required of the borehole sealing system should be informed by the requirements of post-closure performance, rather than by a requirement to return the rock to its pre-drilled condition.
- Post-closure seals in HSR and LSSR should be formed from natural materials; it will not be practicable to demonstrate the required longevity using engineered materials. Bentonite, in a number of physical forms, is a candidate material and has been examined in detail in the laboratory programme undertaken as part of the Phase 2 ‘Sealing boreholes’ project.

- Seals with permeabilities significantly higher than that of the surrounding rock are likely to be acceptable in many cases from a post-closure safety perspective. This means that a range of borehole sealing concepts is potentially acceptable and should be considered.
- Deep boreholes drilled in many geological environments of potential interest to RWM are expected to show significant variability in borehole diameter. This variability will influence the suitability of potential sealing approaches.
- Principles and requirements for selecting post-closure seals have been developed (see Figure 4-1). Candidate materials for post-closure seals in HSR and LSSR have been identified, and a preliminary assessment of their applicability in different settings has been undertaken.
- Potential sealing materials for boreholes in HSR and LSSR have been grouped into the following categories:
    - high density sealing elements, such as high density bentonite blocks;
    - granular materials, such as bentonite pellets;
    - pumpable materials such as bentonite slurries

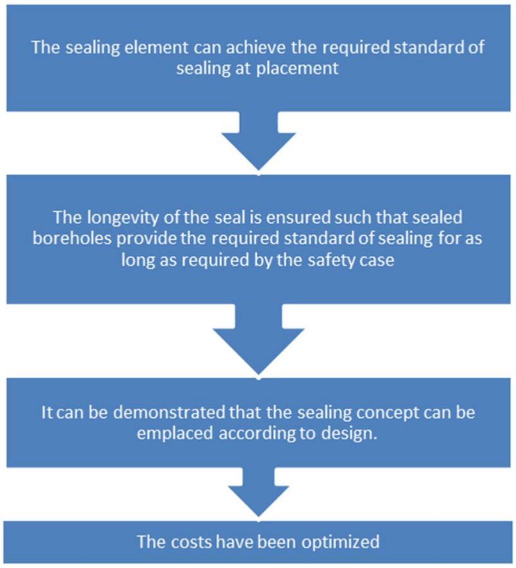

Figure 4-1. Principles and requirements for selecting sealing elements. The top requirement must be met before assessing the requirement at the lower level

5 Placement of bentonite seals in boreholes: knowledge transfer from the oil and gas industry

5.1 Placement techniques used in the oil and gas industry

Brief descriptions of the main techniques used by the oil and gas industry to place materials in boreholes are given below, together with the types of materials that are currently typically placed using each technique.

- **Conventional pumping**: the use of a combination of drilling rig or workover rig, tubing string and high horse power, high rate pump for placing materials in wells. This is the default technique for plugging and abandoning oil or gas wells internationally, used for most wells with few exceptions. The technique is typically used in the oil and gas industry for placing cement-based slurries.

- **Coiled tubing pumping**: the approach is more precise in depth control and has better rate control than conventional pumping. Consequently, the technique has developed significantly over the last decades to place small volumes of materials at specific depths. The technique is typically used in the oil and gas industry for placing cement-based slurries and granular materials (sand plugs).
- **Gravity placement**: the dropping of the material that will form the seal or support element from surface so that it free-falls inside the wellbore intending to land at the bottom of the well. Note that the oil and gas industry still views this approach as being more of an 'art' than a 'science'. The technique is typically used in the oil and gas industry for placement of bentonite pellets for sealing purposes.
- **Dump bailing**: the use of a metallic cylindrical vessel run on wireline or similar containing a small volume of material that can be released at a desired depth either by gravity alone or by positive displacement. The technique is typically used in the oil and gas industry for placing small volumes of cement-based slurries and granular materials (sand plugs).
- **High velocity and high pressure pumping of particulates**: the placement of particulate materials in the wellbore or formation by high velocity or high pressure pumping. The techniques are typically used in the oil and gas industry for placing gravel packs, for hydraulic fracturing and for 'frac-and-pack', which is essentially, a combination of the first two techniques.

Borehole sealing in the oil and gas industry is usually achieved through the use of cementitious materials, although bentonite pellets have been successfully used in recent years to seal near-vertical boreholes up to 1,000m deep [iii,iv]. Consequently, with the exception of gravity placement of bentonite pellets, the oil and gas industry has no direct experience of placing bentonite for sealing purposes in boreholes, though there is extensive experience of pumping bentonite-based drilling muds for viscosity and filtration control [v]. We have therefore considered whether the techniques described above could be used directly or modified to place bentonite, in the form of slurries, pellets and blocks, for sealing boreholes. Potentially suitable techniques are discussed below.

5.2 Potential application of conventional pumping and coiled tube pumping

Both conventional pumping and coiled tube pumping are standard techniques used in the oil and gas industry to place slurries in boreholes. Conventional pumping is the most commonly-used technique for placing cement-based slurries. Coiled tube pumping offers advantages in terms of precision of placement, and is used for placing slurries, as well as for placing granular materials. Although neither technique has been used to place bentonite seals, both could be used to pump bentonite slurries. Bentonite slurries will have lower placed densities, and hence (other things being equal) higher permeabilities, than either bentonite pellets or blocks. It is not clear whether, or under what circumstances, they would be suitable for forming borehole seals. The required permeabilities of borehole seals are considered further in [vi]; in the current paper, we are only concerned with the practicality of approaches to place bentonite in deep (up to 2,000m) site investigation boreholes at a potential GDF site.

5.3 Potential application of gravity placement and dump bailing

Gravity placement is a proven technique for placing bentonite pellets in boreholes up to 1,000m deep. The requirement is that hydration (swelling) of the bentonite pellet is delayed for sufficiently long to allow it to sink to the required position in the borehole; up to one hour sinking time for pellets in a 1,000m deep borehole. Premature swelling can result in bridging of the pellet at shallower depth or spalling, which can further reduce the settling speed and prevent the bentonite from reaching the required depth. The conventional approach to delaying hydration of pellets is through coating them, typically with a water-soluble coating. Commercially-available pellets claim to provide up to 90 minutes protection against swelling. The technique of gravity placement is potentially applicable for use with bentonite pellets in boreholes up to 2,000m deep, although we have been unable to find any examples. The longer sinking time (up to two hours) and greater sinking distance mean there is greater potential for bridging and premature hydration. Gravity placement is also potentially applicable to placing bentonite blocks in boreholes, as illustrated by patents envisaging placement of tapered' bullets' of bentonite.

An aspect of the Phase 2 'Sealing Boreholes' project has been a major laboratory programme to investigate the performance of bentonite (as slurries, pellets and blocks) in a wide range of water compositions. One component of this programme is investigating the early swelling behaviour of coated and uncoated bentonite pellets, to build an understanding of their likely behaviour during placement in a deep borehole. Results indicate that bentonite pellets, even if commercially coated, are physically unstable in highly saline water and their surfaces spall quickly. In such circumstances, gravity placement would not be a suitable placement technique. The outcome of these laboratory studies will confirm the circumstances under which the various placement techniques might be suitable for placing bentonite.

Dump bailers are routinely used to place cement slurries and sand to depths greater than 2,000m in boreholes. The approach may be applicable for accurately placing known volumes of bentonite slurries, pellets or blocks for sealing purposes. One advantage of this approach is that we may be confident that all bentonite has been placed at the required depth, and that no 'bridging' of bentonite at shallower depth is possible. Further, some dump bailers are designed to isolate the contents of the bailer from groundwater as the bailer is lowed in the borehole; the bailer is only opened, and the contents displaced from it, when the bailer has reached the required position. This design feature could be useful as it removes the possibility of premature hydration or spalling of the bentonite pellet or block before the bailer is opened.

There are two potential downsides of using dump bailers, which are being considered as part of the project's forward programme:

- firstly, that only relatively small volumes of material can be placed in currently available dump bailers, though the potential exists for linking two our more dump bailers together to increase the volumes placed on each occasion. Cost is a major consideration in the oil and gas industry, and is the major reason why dump bailers (through the use of multiple trips) are not used to place larger volumes of material in a borehole. This constraint may be less important for sealing boreholes at a GDF site, both because of the relatively small number of boreholes that will require sealing and because of benefits that dump bailers could provide in terms of accurate placement and simplicity of approach, thus enabling correct placement of the seal to be demonstrated;
- second, that some development would be needed to demonstrate that the positive displacement system on a dump bailer would be suitable for pushing bentonite from the bailer into the borehole.

These issues will be considered further in the ongoing programme.

6 Summary and conclusions

Phase 2 of the ‘Sealing boreholes’ project has identified bentonite as a potential material that could be suitable for use in sealing site investigation boreholes associated with a UK GDF. Bentonite is a natural material, and its behaviour over long timescales is understood to the necessary level. Use of cementitious materials for the construction of post-closure borehole seals in the context of a GDF is not recommended. Another aspect of Phase 2 of the ‘Sealing boreholes’ project is to identify suitable materials for constructing the ‘support elements’ of the borehole sealing system (see Section 3). This work, which is in progress, is still considering the potential use of cementitious materials for this role.

Bentonite pellets have been successfully used in recent years by the oil and gas industry to seal near-vertical boreholes up to 1,000m deep; other than this, the oil and gas industry has no direct experience of placing bentonite for sealing purposes in boreholes. As part of the ongoing Phase 2 ‘Sealing boreholes’ project, we have considered the various techniques used by the oil and gas industry for placing other materials (typically cement, sand and ceramic particles) in boreholes and have considered whether these techniques could be used directly or modified to place bentonite, in the form of slurries, pellets and blocks, for sealing purposes.

We have identified conventional pumping and coiled tube pumping as being suitable for placing bentonite slurries but, as noted in Section 5.2, it is not clear whether, or under what circumstances, bentonite slurries would be suitable for forming borehole seals. We have also identified dump bailers as having the potential to place bentonite at higher initial densities, as pellets and blocks. The final phase of the project, to be undertaken by March 2017, will involve recommending a preferred approach or approaches for sealing deep site investigation boreholes in the various geological environments of potential relevance to RWM.

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Posiva Plans And Experiences For Borehole Plugging

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Posiva has developed a theoretical borehole closure design for closure of deep investigation boreholes drilled in Olkiluoto island. These investigation holes have been made from 1989 to date to gather data from the underground disposal facility sites geological, hydrogeological and geochemical features. The data has been used to accept the site for repository location, assess the long-term safety of the site and to design the layout of the repository. These investigation holes will need to be closed at latest when the disposal facility is closed after operation to prevent the formation of preferential flow paths and contaminant transport routes between the ground surface and deposition tunnels/deposition holes. Some holes will however need to be closed sooner. As the need has risen to close certain holes sooner than after operation the borehole closure project has now been reviewed and further work is being designed to modify the theoretical design to implementable one. Now Posiva is planning the practical demonstration to be implemented and used as a borehole closure installation demonstration and test for further development work.

1 Introduction and background

In Eurajoki, southwestern Finland, excavation of an underground investigation facility, ONKALO, is already close to being completed and a spent nuclear fuel disposal facility is under construction after Posiva gained construction license for it in 2015. During site investigations and construction several deep investigation boreholes have been drilled in Olkiluoto island to get information about the bedrock properties. In 2016 the total quantity of these drillholes is 58 with the first made in 1989 and the latest in 2016. The holes vary in diameter, depth, inclination and distance to repository location.

As a part of closure of the underground disposal facility the boreholes, reaching from ground level to repository depth and below, will need to be closed and sealed. This topic has been investigated and tested for example by Posiva and SKB, and for the construction license application an example design was made to present an option for borehole closure (Karvonen 2014).

In 2013 Posiva overcored samples of borehole backfill from borehole OL-KR24 to gain data from material installed in 2005 (Rautio 2006). According to these results and international co-operation Posiva has now revised the design and is currently carrying out a project to change the previous theoretical design to implementable solution. In design of underground disposal facility and Olkiluoto site a need has arisen to close few specific boreholes already during coming years. For this work, the theoretical closure design done for the construction license is now transformed to implementable design for use within next years in tests and demonstrations.

2 Scope and objectives

Scope of borehole closure project is to ascertain that boreholes will not in long-term act as transport routes between repository depth and ground surface. In addition to them being potentially routes for radioactive nuclides, they might also act as routes for dilute waters to penetrate into Olkiluoto bedrock. Both of these two options will need to be hindered.

3 Methods and procedure

Theoretical design (Karvonen 2014) was done using structured selection method for each material placement. Material was defined to be borehole backfill for sparsely fractured, tight rock segments and borehole backfill material was selected to be dense bentonite installed with either basic method or container method. Basic method was designed to be used above depth level above -500 m and container method below that, as in container method the material was installed within a container, safe from erosion caused by water in the boreholes. In basic method the bentonite was installed within perforated copper tube, and thus water could affect it during installation, which could cause erosion. The hydraulic conductivity for the borehole backfill material was set to 10^{-9} m/s conservatively according to underground disposal facility closure design values at repository depth (Sievänen et al. 2012, Dixon et al., 2012).

Parts of the boreholes are not tight, but fractured and having fractures or fracture zones with high hydraulic conductivities. Limits were set that fractured rock was such that had more than 10 fractures per borehole meter, hydraulic conductivity > 10^{-8} m/s, or it was marked in original hole investigations as fractured zone (Ri>RiIII according to Finnish geological mapping system).

The uppermost part of the boreholes was found to be quite insignificant in considering the long-term safety, as the rock is already quite fractured and conductive. There the casings were considered to be left in the holes and a solid rock piece was designed to be installed below casings to slow potential erosion and hamper future drilling possibilities. Above the cylindrical rock piece either concrete or rock material can be installed.

After this theoretical closure design further work has been conducted in the field of borehole closure. In 2013 Posiva overcored borehole backfill and plug samples from OL-KR24 in Olkiluoto, which provided new important data concerning the materials and methods (Karvonen et al. 2015). In 2013 the underground disposal facility closure was modelled with sensitivity analyses also for the borehole closure material.

4 Results from latest investigations

In 2013 the overcoring of OL-KR24 revealed that installed quartz concrete had performed as expected and similar concrete mix can thus be used for fractured rock segments. The bentonite borehole backfill, the primary test material of the project, was also discovered to have sealed to borehole as expected, but the installation method with perforated copper tube delivered a surprise as the copper tube had cracked open vertically for the entire length of the sample. According to visual observations and supporting material tests the water flow had been adequately sealed vertically along the hole despite the breaking of the copper tube (Karvonen et al., 2015). This, however, resulted in recent design change to test a dump bailer in further borehole closure design.

Dump bailer technique uses drilling equipment and a container (dump bailer) to transport dense bentonite to required depth where it can be pushed out of the container. A plate, potentially of copper, acts as the bottom of the container and remains below the bentonite section in the borehole. This technique is already used for example in installing concrete in boreholes and occasionally in oil industry to install bentonite pellets. The swelling of bentonite could jam the material in the dump bailer, but this can be avoided either by coating the bentonite or by making the dump bailer watertight.

Hartley et al. (2014) confirmed by modelling the performance of underground disposal facility closure materials and during that work also made a sensitivity analysis with borehole backfill's hydraulic conductivity of 10^{-5} m/s. Even with this low value the transport routes were found to be limited and only with minor significance for some tens of meter in few specific boreholes. Previous work by Hartley et al. (2012) had modelled the significance of open boreholes (hydraulic conductivity of 10^{-1} m/s) and even that was discovered to be low. With this modelling data it was for implementation decided that the hydraulic conductivity of the borehole backfill could be changed from the theoretical design's 10^{-9} m/s and studies to reason this update are ongoing. Changing the value to slightly more conductive would still keep it within conservative level and provide better sealing function than what was modelled by Hartley et al. (2014).

Uppermost segment of the borehole is still considered by Posiva to be filled with either concrete or rock material. This segment does not have a significant sealing function, but it needs to be filled for it not to remain open. As for dividing the boreholes to sparsely fractured good rock and fractured rock, the theoretical design will be updated to be more robust with longer uniform segments and less material changes. The main hydraulic fractures and fracture zones are separated from each other by borehole backfill segments, but it is not necessary to isolate each small fracture from another. The potential vertical flow is thus prevented with bentonite in good rock segments in strategic, meaningful locations within the borehole.

5 Conclusions

Even though OL-KR24 borehole closure materials and methods were found to have provided a seal within the borehole, the investigation revealed that bentonite may function better without the copper tube. Thus the theoretical design (Karvonen 2014) has now been changed to install bentonite borehole backfill with dump bailer technique instead of basic method copper tubes. Recent modelling has also revealed that hydraulic conductivity of the borehole backfill can be less conservative than it was in the theoretical design. The short altering sections of borehole backfill and plugs will be designed longer and more uniform and critical locations selected for sealing the repository depth for ground surface and significant hydraulic fractures and zones.

6 Acknowledgements

Author wishes to acknowledge the co-operation between Posiva and SKB in borehole closure project, especially Johanna Hansen and Jyrki Liimatainen from Posiva. The work and discussions with all borehole closure group members is highly appreciated.

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Conceptual Sealing Strategy and Initial Performance Assessment for the Chandler Storage and Isolation Facility.

Steve Reece

Tellus Holdings Ltd, Australia.

Tellus Holdings Ltd (Tellus) creates economic, social and environmental value from salt, clay and waste resources. Tellus is proposing to develop an underground rock salt mine with complementary storage and waste disposal business. Products to be stored at the site (surface and underground) include potentially retrievable bulk commodities, equipment, archives and licensed waste storage which could be either retrievable or non-retrievable. The main project site for the underground repository is approximately 120km south of Alice Springs. As part of the incoming supply chain arrangements the project includes a dual use salt and waste storage and transfer facility adjacent to the main Adelaide to Darwin railway line where waste acceptance procedures will be performed.

The project site will develop the 500 million year old Chandler salt bed which is a flat, 800 m deep salt bed with a thickness of up to 300m lying within the Amadeus Basin. The area has been previously explored by deep drilling and seismic survey for oil and gas. In 2013/14 Tellus drilled a number of deep exploration holes and established a 309 million tonnes halite Measured Resource. In 2015 Tellus drilled a further nine holes as stage one of a comprehensive hydrogeological programme to support planning, Environmental Impact Statement activities and a future monitoring programme. The salt to be exploited is of export quality and will be sold into growing Asian markets and the domestic Australian market. Waste will be stored/disposed in packaged form, typically bags, drums and other specialised packages or by hydraulic backfill techniques. It is assumed for planning purposes approximately half of the waste will be placed by hydraulic backfill over the life of the project.

A comprehensive set of trade off studies at FEL 2 level undertaken by multiple specialist parties during 2015/2016 evaluated access to the underground areas of the facility by vertical shafts (common in Europe)or by access by a long driveable decline and ancillary access shafts (common in Australia). Using multi criteria decision analysis (MCDA) the decline access method was ultimately selected however the MCDA score between the two methods were very close, with economic considerations tipping the decision. The underground mining and storage/disposal horizon will utilize a long room and pillar layout extracted by heavy duty drum type continuous miners at a height of approximately 6m.

The demonstration of the long-term containment of underground storage and disposal of wastes in rocksalt is principally undertaken by designating the salt as the barrier rock. The salt due to its low permeability fulfils the requirement of being virtually impermeable to gases and liquids, and of being able to encase the waste because of its convergent behaviour and confining it entirely at the end of the transformation process. The wastes need to be isolated permanently from the biosphere so it is important that the integrity of the geological barrier is maintained and no pathways are formed by which water would be able to contact the wastes, or by which the wastes, or components of the waste, would be able to migrate to the biosphere. To meet this objective it is also imperative to effectively seal any surface to underground connections at the end of the operational phase of the facility which may act as pathways for the ingress of water or brine into the facility and for the release of contaminates.

Tellus has recently undertaken an initial geomechanical stability assessment and site specific risk assessment for both the operational and post-operational phases. The overall approach followed international best practice, in accordance with the requirements of Australian and international regulations, and assessments of underground facilities in countries other than Australia. The assessments have provided confidence that, for the proposed categories of wastes and with appropriate design, operation and closure, there will be no significant risks in terms of the operational and post closure environmental safety of the facility. The paper presented will set out the geological and hydrogeological context for the project, the assumed waste inventory to be disposed and conceptual designs for the facility including the assumed and assessed sealing strategy. Results of the geomechanical analysis, operational and post closure assessments will be presented and conclusions drawn.

8. DOPAS 2016 Seminar Session 4

Session 4 concentrated on the more detailed examination of the plug and seal designs, materials used in the plugs and on the implementation of demonstrations. The presentations provided the audience with case examples of how e.g. the plug location is selected, how to develop and use in design concretes, bentonite and other materials as part of the plugs, and how to install plugs and seals using different DOPAS related or other experiment information.

Chair: Jean-Michel Bosgiraud is a Technological Programme manager at Andra, France, with a background in Mechanical Engineering & Petroleum Engineering. Jean-Michel is currently involved in all the Cigéo related sealing-closure operational and design issues, and as such has participated in DOPAS activities and in previous EC funded projects dealing with buffer material issues (ESDRED and LUCOEX)". He is the Work Package Leader of WP3, Design and technical construction feasibility of the plugs and seals.

Co-chair: Behnaz Aghili Behnaz has a degree in Material Science (M.Sc) in 1986 from Royal Institute of Technology (KTH) in Stockholm, Sweden. And is an expert in concrete material and a project manager at SKB, Swedish Nuclear Fuel and Waste Management Co. She has almost 20 years of experimentation experience in the field of nuclear power both from her time at SKB and also from working at the Swedish Nuclear Power Authority, SSM. She is the Work Package Leader for WP2, Definition of requirements and design basis of the plugs and seals to be demonstrated (DOPAS Project).

Session 4 Schedule and direct links to the DOPAS 2016 Session 4 presentations:

0815-0835	Initial plug and seal design for the Dutch repository concept	Philip J. Vardon[1], Jiao Yuan[1], Michael A. Hicks[1], Yajun Li[1] *[1]Geo-Engineering Section, Delft University of Technology, the Netherlands*
http://www.posiva.fi/files/4154/4.1_Li_Dopas_seminar_Phil_et_al.pdf		
0835-0855	Development and performance of various low-pH cementitious materials for plugs and seals in geological disposal demonstrations (DOPAS Project)	Erika Holt[1], Markku Leivo[1], Tapio Vehmas[1], Jari Dunder[2], Elina Paukku[3], Behnaz Aghili[4], Jiří Svoboda[5], Petr Večerník[6], Xavier Bourbon[7], Sandrine Bethmont[7], Jean-Michel Bosgiraud[7] and Matt White[8] *[1]VTT Technical Research Centre of Finland Oy, Finland* *[2]Posiva Oy, Finland* *[3]Sweco Rakennetekniikka Oy, Finland* *[4]Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden* *[5]Czech Technical University, Czech Republic*

		[6]*ÚJV Řež a.s, Czech Republic* [7]*Andra, France* [8]*Galson Sciences Limited, United Kingdom*
http://www.posiva.fi/files/4155/4.2_Erika_lowpH_Materials_-_Holt_v2.pdf		
0855-0915	FSS (Full-Scale Seal) Experiment transposition from laboratory tests to full-scale emplacement reality (DOPAS Project)	Regis Foin and Jean-Michel, Bosgiraud *ANDRA, F* *rance*
http://www.posiva.fi/files/4156/4.3_Regis_DOPAS_Seminar_Session_4_Transposition_from_laboratory_to_reality.pdf		
0915-0930	Preparations before experiments - production for plug locations for DOMPLU and POPLU (DOPAS Project)	Sanna Mustonen[1] and Pär Grahm[2] [1]*Posiva Oy, Finland* [2]*Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden*
http://www.posiva.fi/files/4157/4.4_Mustonen_DOPAS_slot_excavation_SMRN_240516.pdf		
1000-1020	DOMPLU plug filter and seal design, construction and results (DOPAS Project)	Pär Grahm[1] and Mattias Åkesson[2] [1]*Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden* [2]*Clay Technology AB, Sweden*
http://www.posiva.fi/files/4158/4.5_DOMPLU_Seminar_Session_4_Akesson_update_2016_05_26.pdf		
1020-1035	Bentonite based materials for the Full-Scale Emplacement (FE) experiment: design and production steps	Benoit Garitte[1], Herwig R. Müller[1], Hanspeter Weber[1], Frank Ooms[2], Martin Holl[3] and Sébastien Paysan[4] [1]*National Cooperative for the Disposal of Radioactive Waste (Nagra), Switzerland* [2]*CEBO, The Netherlands* [3]*JRS, Germany* [4]*Laviosa MPC, France*
http://www.posiva.fi/files/4159/4.6_Weber_DOPAS_Seminar_Nagra_Web_final.pdf		

1035-1050	Horizontal bentonite backfilling and concrete plug for the Full-Scale Emplacement (FE) experiment at the Mont Terri URL: requirements, design, instrumentation and emplacement	Benoit Garitte[1],Sven Köhler[1], Herwig R. Müller[1], Toshihiro Sakaki[1], Tobias Vogt[1], Hanspeter Weber[1],Martin Holl[2], Michael Plötze[3], Volker Wetzig[4], Moreno Tschudi[5], Heinz Jenni[6], Tim Vietor[1] Eric Carrera[7], Gerd Wieland[7], Sven Teodori[8], José-Luis García-Siñeriz Martínez[9] and Frank Jacobs[10] [1]*National Cooperative for the Disposal of Radioactive Waste (Nagra), Switzerland* [2]*J.Rettenmaier & Söhne, Germany* [3]*ETH, Switzerland* [4]*VersuchsStollen Hagerbach, Switzerland* [5]*Belloli, Switzerland* [6]*Rowa, Switzerland* [7]*Amberg Engineering, Switzerland* [8]*ÅF-Consult, Switzerland* [9]*AITEMIN, Spain* [10]*TFB, Switzerland*
http://www.posiva.fi/files/4160/4.7_Garitte_2016_05_26_FE_emplacement_DOPAS.pdf		
1050-1110	Hydro-mechanical and chemical-hydraulic behaviour of different types of shaft sealing materials (DOPAS Project)	Oliver Czaikowski, Kyra Jantschik, Helge C. Moog, Klaus Wieczorek and Chun-Liang Zhang *Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Braunschweig, Germany*
http://www.posiva.fi/files/4161/4.8_Czaikowski_160526_dopas_seminar_cza.pdf		
1110-1130	Performance of Czech Bentonite Material in the Plug in Geol ogical Disposal Demonstrations.	Večerník Petr[1], Vašíček Radek[2], Šťástka Jiří[2],Trpkošová Dagmar[1], Havlová Václava[1], Hausmannová Lucie[2], Smutek Jan[2], S voboda Jiří[2] and Dvořáková Markéta[3] [1]*ÚJV Řež,; Czech Republic* [2]*Czech Technical University, Czech Republic* [3]*SURAO, Czech Republic*
http://www.posiva.fi/files/4162/4.9_Vecernik_DOPAS_performace_of_Czech_bentonite_final.pdf		

Initial Plug and Seal Design for the Dutch Repository Concept

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In the Dutch repository concept, that is geological disposal in Boom Clay, plugs are proposed to be used to hydraulically seal off disposal drifts after the emplacement of waste packages and to restrict any movement of backfill. This paper presents an initial scoping of the design requirements for plugs and seals in this context and initial scoping calculations are carried out for the specific conditions expected in the Dutch geological context. It is intended to provide an initial design and approximate sizing and a commentary on the key issues, so that detailed design and performance assessment may be carried out. The design of the plug system has been split into two parts, (i) a compacted bentonite seal, designed primarily to restrict the hydraulic flow, and (ii) a concrete plug, designed to restrict any movement of the backfill. Two outline designs have been produced, one where the tunnel lining is removed to allow the concrete plug to bear on the lining and the second where the lining is not removed and frictional resistance is the main support. The initial sizing of the concrete plug leads to a plug length of 2.85 – 4.8 m for the design where the tunnel lining is not removed and 0.99 – 1.67 m where the tunnel lining is removed, depending on the tunnel radius (1.1 to 1.85 m). This length could be further reduced by the addition of shear reinforcement. The bentonite seal has been designed so that the swelling pressure is able to re-seal the EDZ and provide good sealing. Numerical modelling has shown the length required to prevent significant axial flow is between 0.5 and 1.0 m.

1 Introduction

To control water flow and restrict material movement in tunnels, such as mines, or in the case of a geological disposal repository, plugs and/or seals can be used. As part of the backfill of the repository, plugs are likely to be required. In the Dutch repository concept, plugs are proposed to be used to hydraulically seal off disposal drift after emplacement of waste packages and to restrict movement of backfill.

Based on the required functions of the plug system, two main components for a plug system in Boom Clay are summarised as follows: a concrete plug and a bentonite seal. The concrete plug should mechanically support the bentonite seal and backfill, and transfer the loads into the surrounding host rock. The bentonite seal cannot prevent leakage unless it has reached sufficient saturation, so the concrete plug must prevent leakage until this time (Dahlstrom, 2009; Malm, 2012). After this point, the requirement of the concrete plug to be watertight is no longer necessary. The concrete plug must carry the hydrostatic water pressure as well as the effective stresses.

The backfill is likely to provide a low permeability environment itself, but to reduce any risk of erosion of the backfill, the seal should consider only allow a low gradient to exist in the backfill.

The bentonite seal shall prevent axial flow from the deposition tunnel, and heal cracks that may initiate on the upstream side of the concrete plug and therefore prevent leakage. The bentonite seal is designed to have a low hydraulic conductivity, it should swell and seal all passages and it must be able to withstand a high hydraulic gradient. The bentonite seal should have good contact between the clay host rock and the bentonite seal. In order to cut off water flow through the EDZ, the bentonite seal can be inset in a slot into the host rock or may be able to reseal the EDZ via swelling behaviour. The hydraulic cut off is achieved by lowering the hydraulic conductivity of the clay around the seal to a value lower than the undisturbed in-site hydraulic conductivity (Van Marcke et al., 2013). In addition, the bentonite seal should also heal cracks that may initiate on the upstream side of the concrete plug, and thereby prevent leakage from the deposition tunnel.

2 Conceptual design of the plug geometry

Two types of conceptual plug design are studied in this paper, some basic calculations are carried out to determine the plug length and strength, from the hydraulic and mechanical point of view. The two plug systems are shown in Figure 1(a), where in Design A the concrete plug is installed inside the tunnel lining, whereas in Design B the tunnel lining is removed for the concrete plug to be installed. In both designs the tunnel lining is removed in the location of the bentonite seal, to ensure good connection between the bentonite and the Boom Clay. It is anticipated that the EDZ would be able to be sealed via swelling pressure of the bentonite, but local over-excavation in this area would allow additional reduction of hydraulic conductivity.

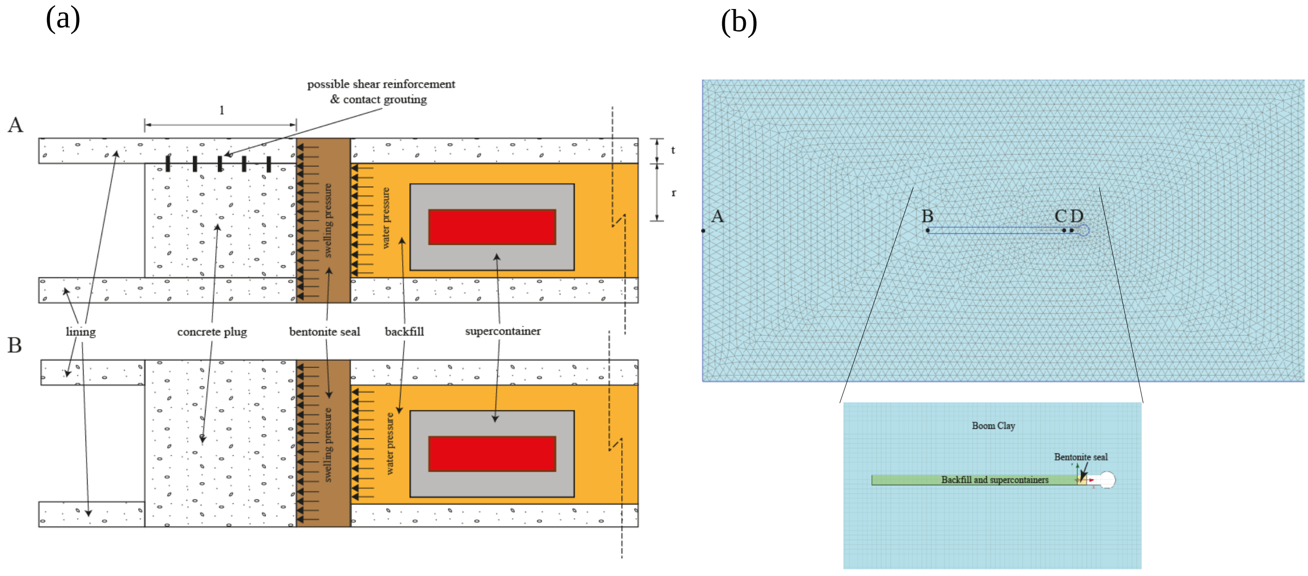

Figure 1. (a)Two types of conceptual plug system design; A: with the concrete plug installed inside the tunnel lining, and B: with the tunnel lining removed locally where the concrete plug is installed and (b) The mesh and details of the deposition tunnel and plug system used for the hydraulic simulation

In Design A the mechanical loads must be withstood via friction between the tunnel lining and the plug, whereas in Design B the plug can transfer loads via compression into the lining (and subsequently the rock). In both cases, the concrete is designed to be unreinforced to reduce the possibility of metal corrosion and for the same reason neither design A nor design B has access tubes. Moreover both designs do not require alteration to the tunnel construction via tapering or substantial over-excavation.

3 Mechanical stability

For the first type of plug design (shown in Figure 1(a) type A), the failure of this parallel-sided plugs is governed by the interface shearing between concrete plug and lining. The following equation can be applied to calculate the circular plug length *l*, of radius *r* (Auld, 1983),

$$l \geq \frac{\sigma r}{2 p_{pe}} \tag{2.1}$$

where σ is the applied stress, in this case the total stress, is assumed to be 7 MPa. This is the sum of the estimated swelling pressure in the backfill of 2 MPa (Fälth and Gatter, 2009) and a pore-water pressure of 5 MPa at the depth of 500 m (Arnold et al., 2015; Verhoef et al., 2011); and p_{pe} is the permissible punching shear stress of the rock or concrete interface. It may be possible to reduce this length by incorporation of shear reinforcement (as shown in Figure 1(a) type A), but this has not been considered in this scoping calculation.

For the design of the type B plug, the resistance force is provided by the interface shearing between concrete plug and host rock and support from the lining. In addition the plug itself must be able to support the generated shear within the plug. It was found due to the thickness considered for the lining (~0.5m) that the punching stress through the plug is the dominant mechanism. This can be considered via the following equation (Auld, 1983),

$$\sigma_p = \frac{\sigma \pi r^2}{2\pi r l} \leq p_p ; l \geq \frac{\sigma r}{2 p_p} \tag{2.2}$$

where σ_p is the punching stress and p_p is the permissible punching stress of the concrete.

Utilising EN1992-1-1 (European Committee for Standardisation, 2004) to derive the appropriate concrete strength measures and using concrete class C55/67, the permissible punching shear stress of the rock or concrete interface, p_{pe}, is 1.35 MPa and p_p is 3.87 MPa.

For design A, applying equation (2.1) and considering the inside radius of the tunnels r = 1.85 m for LILW and (TE)NORM disposal gallery and r = 1.1 m for HLW/spent fuel disposal gallery (Verhoef et al., 2011), would give a plug length of 4.80 m and 2.85 m, respectively.

For design B, and applying equation (2.2) gives the plug length of 1.67 and 0.99 m for radius of the tunnel of 1.85 m and 1.1 m, respectively.

4 Hydraulic seal of the plug system

Two-dimensional plane strain analyses have been performed with PLAXIS 2D AE (Plaxis, 2014) to investigate the hydraulic performance of the seal component of the plug system. The objective is to investigate the length at which flow is reduced to a minimum and pressure gradients in the backfill are reduced to reduce erosion.

The simulation domain is approximately 200 m long and 100 m high, with the mesh and geometry near the deposition tunnel and plug system shown in Figure 1(b). The domain is discretised using 15-node triangular elements and refined in close vicinity of the tunnel (Figure 1(b) top). The hydraulic boundary conditions are as follows: the water head at the outer Boom Clay boundaries are fixed to 500 meters, the inner boundary of the open tunnel and the outer sealing boundary are free draining, i.e. fixed of 0 m head.

The domain is divided into 3 different property areas with different hydraulic properties, (i) those of the host rock (Boom Clay), (ii) backfill and supercontainers, and (iii) the bentonite seal (Figure 1(b) bottom). The fluid flow has been modelled here using a steady state Darcy flow equation. The mechanical behaviour and displacements in the domain have not been included in the simulations. Since the backfill material for the Dutch disposal project has not been fully specified, two values of hydraulic conductivity are used in the simulations representative of foamed concrete, the proposed backfill material, or sand. The hydraulic properties of the different materials are: k = 10^{-9} m/s and 10^{-10} m/s for backfill, 10^{-13} m/s for bentonite and 10^{-12} m/s for the Boom clay. In order to find the optimal bentonite seal length, the hydraulic response of five different length seals, L={0.1, 0.5, 1.0, 2.0, 5.0} m, are studied.

Figure 2(a) shows the pore water pressure head distribution in the calculation domain with backfill hydraulic conductivity, k=10^{-9} m/s (left-hand side) and k=10^{-10} m/s (right-hand side), for various seal lengths. An increase in seal length, reduces the low pore water pressure head zone. The reduction in the backfill hydraulic conductivity also results in a reduction in the low pore water pressure head zone. Figure 3 shows the pore water pressure head profile along the line AD (see Figure 1(b)) with backfill hydraulic conductivity k=10^{-9} m/s and k=10^{-10} m/s, for various seal lengths. As can be seen, the pore water pressure head at points B and C increase with increasing length of the bentonite seal. Overall, the pore water pressure head gradient is mainly taken by the bentonite seal, only a small part is taken by the backfill, which reduces the likelihood of erosion.

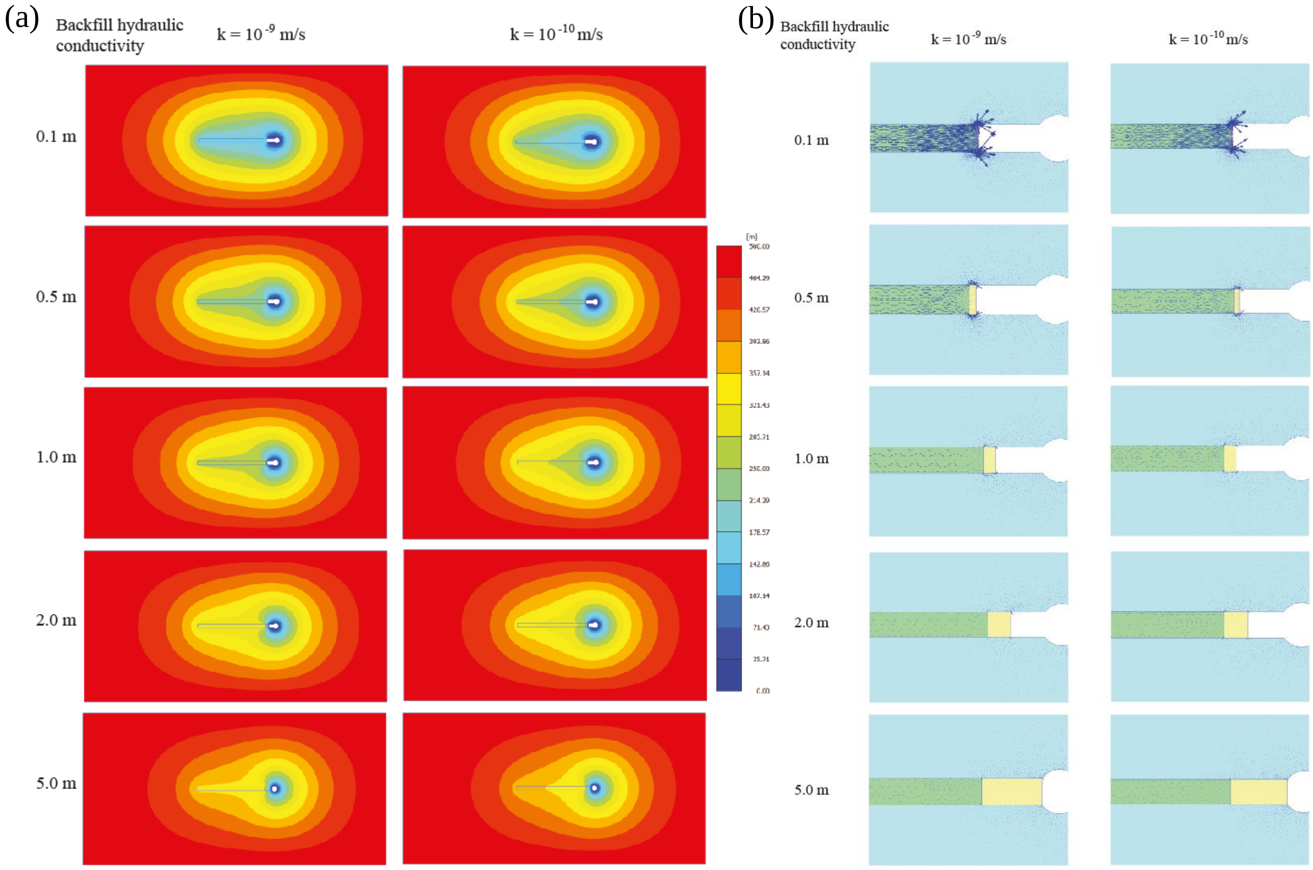

Figure 2. (a) Pressure head distribution for different sealing length, left: k=10^{-9} m/s of the backfill hydraulic conductivity; right: k=10^{-10} m/s of the backfill hydraulic conductivity and (b) Velocity distribution near the plug for different sealing length, left: k=10^{-9}m/s of the backfill hydraulic conductivity; right: k=10^{-10} m/s of the backfill hydraulic conductivity

Figure 3 also shows that with lower backfill hydraulic conductivity, the pore water pressure head gradient in the rock decreases, which indicates a lower backfill hydraulic conductivity results in better sealing, however the gradient in the backfill is greater, indicating a greater chance of erosion. Figure 4(a) shows the percentage of water head gradient taken by the bentonite seal (Point C) over the water head at end of the disposal tunnel (point B) as a function of plug length, for different backfill hydraulic conductivity. These plots shows that for different backfill hydraulic conductivity the percentage of water head at B/C have similar trend. The optimal seal length can be conducted to be between 0.5-1.0 m, since any further increasing the seal length only slightly increases the percentage of water head at B/C.

The velocity of water flow close to the disposal tunnel and the plug system is shown in Figure 2(b), for two different backfill hydraulic conductivities, and for various seal lengths. The results from calculations with k=10^{-9} m/s and k=10^{-10} m/s are similar, with the major flow paths in the host rock around the seal. In both cases increasing the plug length results in decreasing velocity around the plug system. As seen from Figure 2(b) the maximum flow velocity located near the top and bottom of the plug, which indicated those areas may be the weak zone, reinforcement could be useful, e.g. by extending the bentonite seal into the host rock. At seal lengths over 1 m, axial flow is virtually eliminated and almost no preferential flow around the seal is seen. Figure 4(b) shows the maximum velocity in the domain versus seal length for different backfill hydraulic conductivities and reinforces this finding. It is seen that the optimal plug length located between 0.5-1.0 m, with further increases in length not resulting in substantial decreases in flow.

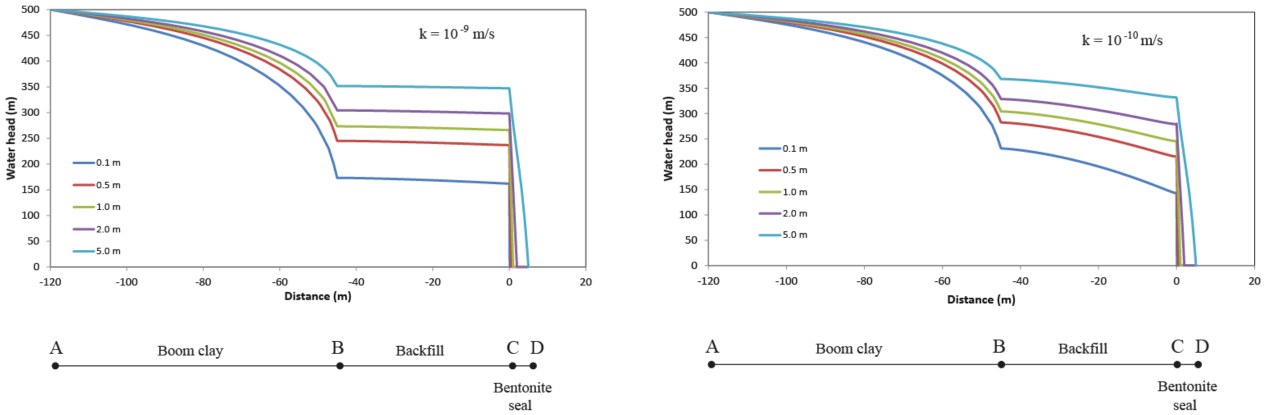

Figure 3. Pressure head distribution along the tunnel for different sealing length, left: k=10^{-9} m/s of the backfill hydraulic conductivity; right: k=10^{-10} m/s of the backfill hydraulic conductivity

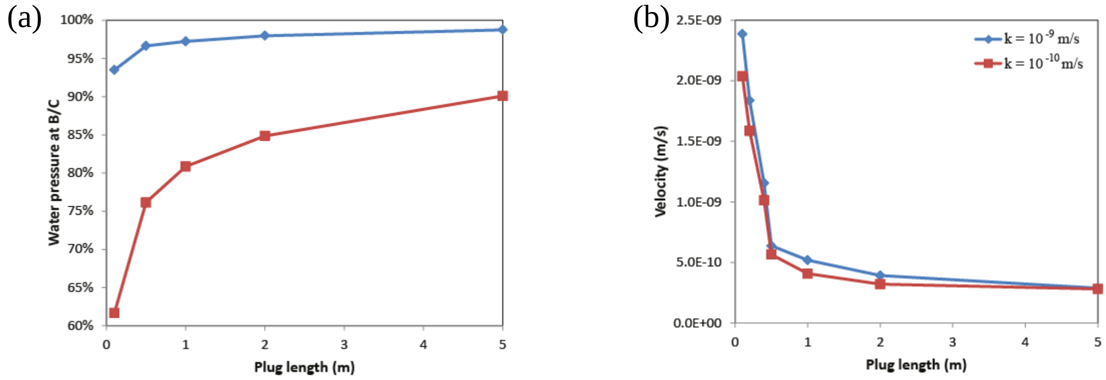

Figure 4. (a) Percentage of water head taken by the plug verses sealing length for different backfill hydraulic conductivity; (b) Maximum velocity in the domain versus sealing length for different backfill hydraulic conductivity

5 Conclusions

Two main requirements for the plug system for the Dutch geological repository have been distilled: i) a plug that keeps the backfill in place and ii) a seal that prevents axial water flow. The system shall prevent erosion of backfill so that the backfill maintains its function.

Two types of conceptual mechanical plug design have been studied. One where linings are locally removed and the second where they have not. The plug lengths in all cases considered are thought to be reasonable, being in the range of the radius. With the conceptual design A leading to a plug length of 2.85 – 4.80 m and conceptual design B leading to a plug length of 0.99 – 1.67 m. From the mechanical point of view, removing tunnel lining segments leads to significantly reduced plug length (conceptual design B), but this may lead to a more difficult construction process.

A bentonite seal has been chosen to hydraulically seal the plug system, when bentonite is hydrated, the swelling pressure exerted against the clay will locally lower the hydraulic conductivity of the clay and close any cracks present around the bentonite seal. An appropriate length was shown to be approximate between 0.5 and 1.0 m. Close contact with the rock is required to ensure a good seal, therefore the tunnel lining should be removed in this location. The bentonite seal could additionally be inset in a slot with a minimum depth larger than the depth of EDZ to ensure good sealing.

6 Acknowledgements

The research leading to these results has received funding from the Dutch research programme on geological disposal, OPERA. OPERA is financed by the Dutch Ministry of Economic A airs and the public limited liability company Elektriciteits-Produktiemaatschappij Zuid-Nederland (EPZ), and is coordinated by COVRA.

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Development and Performance of Various low-pH Cementitious Materials for Tunnel End Plugs in Geological Disposal Demonstrations

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Tunnel end plugs and shaft seals of nuclear repositories may use low-pH cementitious materials to maintain the safety functions of the engineered barrier systems. Low-pH materials can be used for concrete containment walls of the plug, tunnel shotcrete and rock/bolt injection grouts used for mechanical stability and hydraulical isolation in the repository. The need for using low-pH materials (pH typically under 11 in leached water) rather than traditional concrete (pH about 13) is governed by the impact of leachate on long-term performance of bentonite clay within the engineered barrier systems (EBS) or plug seal. Within the DOPAS full-scale demonstration experiments of Finland (POPLU), Sweden (DOMPLU), Czech Republic (EPSP) and France (FSS), various low-pH materials formulations were used and lessons learned regarding their implementation. Example recipes are presented together with their performance characteristics and lessons learned during emplacement and monitoring. Detailed analysis about the total plug concrete performance is outside the scope of this paper, yet may be shared in other papers within the same DOPAS Seminar (i.e. by Posiva, SKB, SURAO, Andra and others).

1 Introduction

Concrete plugs, containment walls, shotcrete and injection grouts may need to be made of cementitious materials that produce a low-pH plume in the order of 11or less, in order to maintain the swelling capacity of the bentonite clay used within engineered barrier systems (EBS) of a nuclear waste repository. Such products made of cement alone will have a pH on the order of 13, which can create leachate endangering the bentonite, thus alternative binders of silica fume, fly ash and/or blast furnace slag are used as cement replacements. The low-pH concrete will also have low heat-of-hydration and possibly a delayed setting time, yet all other performance characteristics can be engineered to be comparable to traditional materials. Much work has been done in past years on the development of low-pH cementitious materials [Martino 2011, Vogt 2009], yet these recipes and performance must always be validated for the local conditions based on available suitable materials, environmental exposure classes and performance requirements. Such work was undertaken in DOPAS, to provide a wider range of low-pH materials that can be adapted to other programs and applications in the future.

2 Objectives

Four of the five full-scale plugs and seals demonstrated in DOPAS have utilized low-pH materials. The performance requirements of the concretes have differed slightly, but there are also many similarities between the mixtures used. The targets for the mixture are to have low pH, low heat, low shrinkage, high workability and in many cases also good durability especially with regard to watertightness. Applying traditional concrete design methods and durability requirements according to international standards, these properties are challenging to simultaneously achieve.

All of the experiments undertook laboratory development programs to establish the suitable mixture proportions, for instance the suitable binder content (kg/m^3), gradation of aggregate, water-to-binder (w/b) ratio and dosage of admixtures. Properties under evaluation have included early age or fresh mixture properties of workability and flowability, open or workable time until setting, segregation risk and heat of hydration. Once a suitable mixture has been found, samples were made for assessing longer-term properties. These tests have included compressive and tensile strength, watertightness (permeability), drying and autogenous shrinkage, and leachate for pH assessment at various ages from 7 days to 1 year or more.

After suitable laboratory mixtures were found for the specific experimental application, larger-scale trials were done at ready-mix supplier companies to evaluate consistency when upscaling. In some cases, such as POPLU, method tests were done above or underground to further demonstrate the suitable mixture and construction techniques. This was also beneficial for practicing the delivery sequence and quality control methods that would be used for the actual plug construction.

Finally low-pH concrete and shotcrete was used in the full-scale demonstrations of DOPAS. Quality control samples were made to show conformance with the specifications, laboratory trials and design basis. The results from the demonstrations are used to validate the safety of the plugs, especially with regard to watertightness and the durability for the intended service life.

3 Materials & Methods

All of the low-pH concrete mixes applied a common approach in mix designs by substitution of cement used in high-pH concretes with silica fume, blast furnace slag, and/or fly ash, with the addition of fine aggregate filler. Some recipes were a binary blend (cement plus one substitute), while others were ternary blends (cement plus two substitutes). Aggregates and binders were locally sourced. and had to be tailored to the boundary conditions of the experiments (e.g., dimensions and positioning of other structures such as reinforcement and monitoring systems influenced maximum aggregate size or emplacement techniques). It should be noted that in some cases, such as POPLU, extra precautions about foreign materials acceptance were done so as not to harm the site [Posiva 2014], which posed limitations on the use of materials such polycarboxylate-based superplasticizers. Table 1 shows the comparison of mixture designs used in the four experiments.

Examples of the methods used for assessing early age performance of the low-pH materials include: workability (Slump EN 12350-2, Slump flow with t500 by EN 12350-8 or EN206-9, Flow table EN 12350-5, Rheology using a Contec 5 –viscometer); air content (pressure method EN 12350-7); density (EN12350-7); setting time (penetration resistance Finnish SFS 5289); segregation (visual inspection, microscopy of hardened cubes); heat of hydration (semi-adiabatic for concrete RILEM

TC119-TCE1, isothermal for paste by TAM-air). These tests were performed on multiple batch tests in order to establish suitable proportions.

Examples of the methods used for assessing long-term performance of the low-pH materials include: compressive strength (EN12390-3); density (EN12390-9); flexural strength (EN 14488-3); splitting tensile strength (EN12390-6); elastic modulus (Finnish method SFS 5450); watertightness (pressure test EN12390-8); water permeability (EN17892-11); shrinkage (autogenous and drying shrinkage from 1 day onwards) and creep; chloride diffusivity (non-steady state chloride migration by NT Build 490); sulphate resistance (scaling and loss of strength after exposure to Na_2SO_4 ; $MgSO_4$); pH leachate (in deionized water and simulated groundwater according to [Alonso 2012]. These tests were performed on select mixtures for validation of design basis and performance requirements.

Table 1. Low-pH mix proportions used in the DOPAS Project full-scale demonstrators. Some aspects of the concrete recipes are confidential and are not, therefore, reproduced here.

	FSS SCC	FSS Shotcrete	EPSP Shotcrete*	DOMPLU SCC	POPLU SCC**
Cement	CEM III/A 52.5 130 kg	CEM I 52.5 190 kg	CEM II / B – M (S-LL) 42,5 N	120 kg/m^3	106 kg/m^3
Silica Fume	130 kg	190 kg	Yes (approx. 1:1 to cement)	80 kg/m^3 ***	89 kg/m^3
Fly Ash	-	-	-	-	85 kg/m^3
Slag	-	-	-	-	0
Water	204.1 kg	200 kg	Yes	165 kg/m^3	128 kg/m^3
Limestone or Quartz Filler	408.4 kg	-	-	369 kg/m^3 (limestone)	115 kg/m^3 (quartz)
Sand	698.7 kg	1 347 kg	Yes	1037 kg/m^3 (natural sand 0-8 mm)	929 kg/m^3
Gravel	682.1 kg	408 kg	Yes	558 kg/m^3 (8-16 mm crushed granite)	911 kg/m^3
Super-plasticiser	2.2%	3.4%	SIKA 1035CZ	6,38 kg/m^3	18,6 kg/m^3
Retardant	0.1%	0.7%	SIKA VZ1	0	0
Glass fibres			crack HP (Sklocement Beneš)		
Water-cement ratio				1,375	1.20
Water-binder ratio				0,825	0.46
Water-powder ratio***				0,290	0.28

Notes:
** EPSP Shotcrete - exact proportions are proprietary information of supplier*
*** POPLU SCC recipe provided for mass used in plug section #2 with 32 mm maximum aggregate size mixture*
**** DOMPLU Silica fume: in powder form in laboratory, as slurry in large-scale in-situ castings*

4 Results & Discussion

Each of the full-scale experiments of Finland (POPLU), Sweden (DOMPLU), Czech Republic (EPSP) and France (FSS) were successful in emplacing the various low-pH materials formulations in-situ. The volume of materials and key results from field demonstration quality control are given in Table 2. It should be reminded that the results cannot be directly compared between mixtures, because each experiment had a different set of requirements for the low-pH material. An example of the appearance of fresh self-compacting concrete and quality control blocks from POPLU are given in Figure 1 and Figure 2 respectively. Examples of DOMPLU and EPSP casting are shown in Figures 3 and 4 respectively.

Full details of results for each experiment can be found in the DOPAS summary reports [Grahm 2015, Holt 2016, SÚRAO 2016, Andra 2016].

Amongst the key properties of concrete used in plugs and seals are compressive strength, pH of leachate and curing temperature. High compressive strengths of ~40-60 MPa could be achieved for concrete mixes applied in all of the experiments. In FSS, the shotcrete used had a relatively low compressive strength of ~24 MPa, whereas the concrete used in EPSP, which incorporated glass fibres for additional strength, had a compressive strength of ~55 MPa. The compressive strength and tensile capacity of the concrete used in POPLU was provided by a combination of the concrete and the reinforcement, whereas DOMPLU was built without steel reinforcement bars.

Table 2. Low-pH material amounts used in full-scale experiment and some of the quality control key parameters (average values).

	FSS SCC	FSS Shotcrete	EPSP Shotcrete	DOMPLU SCC	POPLU SCC
Material amount emplaced (m^3)	250	250	80	94	178
Slump (mm)	-	±20	180-260	-	-
Slump flow (mm)	>80	-	350-590	643	605
Density (kg/m^3)	2253	-	2200	2210	2356
Air content (%)	-	-	-	7,2	1,7
Maximum temperature in-situ (°C)	48	67	53	9,3	43
Compressive strength (MPa), at 91 days	> 43	41.5 (28d)	> 50	82,2 *	83 **
Flexural strength (MPa)	-	-	>5	-	-
Watertightness (mm), at 91 days	-	-	-	-	2,1
Water permeability (m/s)	-	-	$<10^{-11}$	-	-
pH leachate, 91 days in groundwater	10.3	10.4	11.3	-	10,8
t_{500}				3,2	

Notes:

** DOMPLU: Tested on cylinders drilled from the 1m³ monolite casted at the same time and with same material as the plug.*

*** POPLU: Tested on quality control 15cm cubes cast at the same time as the plug, stored underground.*

Figure 1. Appearance of POPLU ternary mixture, during field quality control testing.

Figure 2. Example of 1m^3 quality control blocks produced with POPLU experiment.

Figure 3. Checking t500 during DOMPLU slump flow test, field quality control.

Figure 4. Shotcrete of EPSP plug.

Challenges encountered during the emplacement of the concrete mixes have been overcome:

- The approaches used in DOMPLU allowed for addition of superplasticiser to the mixture following acceptance testing in order to ensure the appropriate rheological characteristics for the concrete.
- In FSS, the preparation of concrete mixes at the concrete plant had to be scrutinised and monitored to ensure compliance with the mix specification, for example to check the homogeneity of the dry material mixture.
- Posiva was able to tailor their new ternary mix design of the low-pH concrete mix used in POPLU to the specific conditions of the experiment, especially the nature of the congested reinforcement used in the concrete wedge and the type of superplasticiser.
- For EPSP the logistics (transport of concrete in the underground) has been the main issue limiting the speed of emplacement. Further work also needs to be done on lowering of the concrete pH.

However, there is further work to be undertaken on low-pH concrete mixes. Additional work should be done to evaluate the sensitivity of the concrete performances to marginal variations in component percentages and infer, by so doing, how robust a given mix can be. The role of certain additives e.g., plasticisers should also be further explored to see how dependant on the ratio between organic and mineral components a concrete mix composition can be. This is necessary to better assess the robustness of the safety demonstration (i.e. determine the role of complexing products in long-term safety). All of the concrete mixes used in the DOPAS Project experiments are novel materials, and, therefore, are not yet compliant with existing standards.

Testing of the B200 mix used by SKB and the ternary mix by Posiva has indicated that the shrinkage of the concrete may be less than expected. For SKB's case, this may mean that it will not be necessary for the concrete to fully release from the rock for curing to occur without significant crack formation. The monitoring of the DOMPLU experiment concrete dome will contribute to further understanding phenomena related to concrete shrinkage and performance and also help to determine whether further work is needed on the shrinkage characteristics and release requirements.

The DOPAS Project experiments have demonstrated that reinforced and non-reinforced low-pH SCC can be emplaced successfully in repository-like conditions. The POPLU project has shown that self-compacting concrete can be achieved where no vibration is needed to emplace the material in the mould, thus a longer plug section could be envisioned as feedback to the design basis.

5 Conclusions

A range of low-pH cementitious mixes has been developed from lab through full-scale for application in repository plugs and seals. The recipes were tailored to meet early age and long-term performance, considering the construction methods for material emplacement and structural design basis. All the experiments were successful in up-scaling mixtures and emplacing the demonstrations in-situ. Monitoring and quality control testing provided verification of performance and yielded valuable lessons that can be integrated in the future and by other waste management programs utilizing low-pH cementitious materials.

6 Acknowledgements

We grateful acknowledge the many researchers, engineers and contractors who assisted in designing and conduction performance verification tests on the low-pH materials used in the DOPAS experiments.

The research leading to these results has received funding from the European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013 under grant agreement no 323273, the DOPAS project. Complimentary funding provided by partner organization of Posiva, SKB, Andra, UJV, CTU and VTT which has contributed to the results in this paper are also acknowledged.

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FSS (Full Scale Seal) Experiment
Transposition from laboratory tests to full scale emplacement reality
DOPAS 2016 SEMINAR

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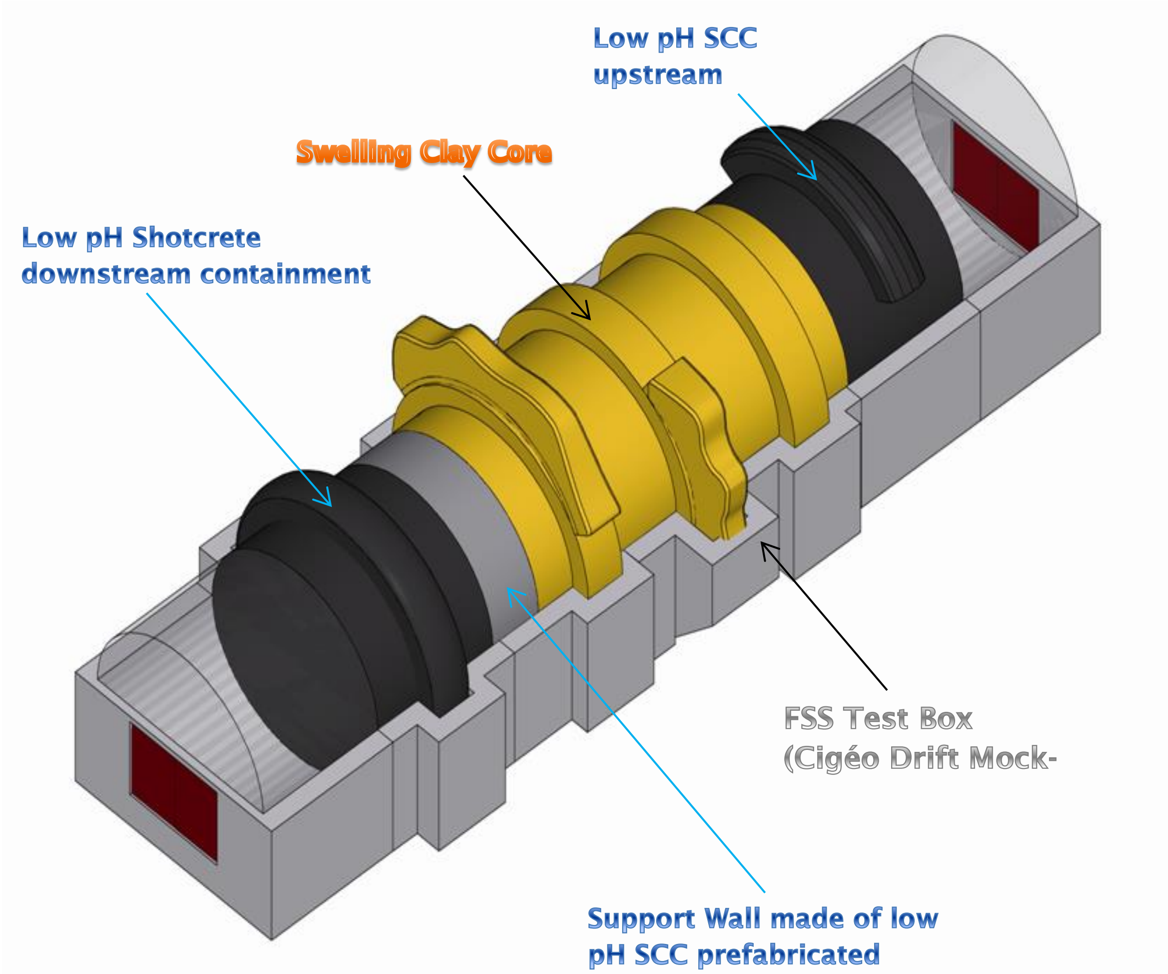
----SUMMARY----

The objectives of this topic is to show the main difficulties encountered by Andra in the FSS experiment to comply with the specified requirements regarding the construction of the swelling clay core and the construction of its 2 containment walls (one with low pH SCC and the other one with low pH shotcrete), in relation with (in particular) the scale aspects.

The differences between the results of the upstream containment wall built with SCC and the downstream one built with shotcrete will be analysed and possible solutions to reach a better result will be suggested. For the filling of the bentonite core, the different difficulties appeared during the construction phase will be also analyzed and possible solutions to reach a better final dry density will be listed.



1. Introduction

The Full Scale Seal (FSS) experiment, which is part of the DOPAS project, is one of various experiments implemented by Andra, within the frame of the Cigéo Project (the French Deep Geological Repository) development, to demonstrate the technical construction feasibility and performance of the seals to be built at time of closure of the various repository components (shafts, access ramps, drifts, disposal vaults).

FSS was built inside a drift model constructed in a hangar, on surface, for the purpose. The dimensions are close to the actual dimensions of the deal structures to be built in Cigéo (approximatively with the same diameter, but with a shorter length). To build this seal prototype, Andra specified to the contractors different requirements to be fulfilled in the emplacement of the bentonite core or in the construction of its associated low pH concrete containment walls.

A French laboratory (CEA/LECBA), a member of the consortium of companies contracted, developed the various materials (low pH self-compacting concrete (SCC), low pH shotcrete and bentonite admixture) necessary to backfill the drift mock-up in accordance with predetermined specifications. All these materials were initially designed and tested at a small scale (laboratory test size) to validate the results at this scale. In parallel backfilling methods, and means, were designed jointly by the four members of the consortium (CEA/LECBA, LAVIOSA: a company specialized in bentonitic products, EIFFAGE TP in charge of the emplacement and SOLEXPERTS in charge of instrumentation), in accordance with their pre-existing knowhow and with the results obtained in preliminary laboratory studies. Afterwards, during the FSS mock-up backfilling with the different materials and following the different measurements carried out during advancement or post construction, it was shown that the real results were not in total accordance which those expected.

This presentation will show the influence of scale effects between the initial design and the final emplacement case for the bentonitic materials and cementitious materials used for the FSS experiment and how this situation has modified the design basis or the requirements of the Cigéo seal concept.

2. Scope and objectives of FSS

2.1 General objectives

The FSS experiment is one piece of a set of tests, designed to demonstrate the industrial feasibility of the drifts seals to be built for long term safety of Cigéo. The objectives specifically designated for this experiment, were:

- To show the industrial feasibility of emplacing large volumes of bentonite (core) and low pH concrete (containment walls) that correspond to a full scale seal of a drift in the Cigéo Project (order of magnitude: decametric diameter and multi-decametric length). The practical modalities to use these materials have to guarantee the achievement of specified requirements of the core and of the containment walls.
- To define the operational requirements useful to obtain the properties (especially mechanical and hydraulic ...) expected; for example, requirements for tolerances on the bentonitic material dry density distribution inside the core.
- The decametric size of the experiment does not permit to envisage a total and complete re-saturation of the core to check its swelling and permeability; this information has to be obtained from another test at a smaller scale (REM presentation – cf. Nathalie Conil et al.).
- To define and deploy the control means of monitoring during filling operations, to verify the compliance of the implementation of the materials in relation with defined requirements.

- To define and deploy the control means to verify "post-mortem" that the objectives are fulfilled; e.g. thorough filling (before swelling takes place) of the upper parts of the seal (which are also called recesses and are sections simulating the partial deposition of the drift concrete liner).

In parallel with the drift mock-up construction which was not a construction objective but just a tool useful to simulate a drift in which the full scale seal could be emplaced, the main challenges were to elaborate the 2 low pH concrete formulations and bentonite material mix to reach the expected requirements.

2.2 Low pH self-compacting concrete and shotcrete requirements

For these materials the most important requirements were:

- The low pH value to reach;
- The period of use of the material.

For the period of use, the need was to wait 2 hours before emplacement (SCC or shotcrete) to simulate the transport duration between fabrication at the surface and casting underground. The table below shows the main requirements concerning the low pH SCC and shotcrete to be emplaced in the 2 containment walls of FSS (SCC upstream and shotcrete downstream).

Upstream containment wall		Downstream containment wall	
SCC (Self Compacting Concrete)	**Injection grout**	**Precast concrete blocks**	**Shotcrete**
pH of poral solution (28d) ≤ 11.0 (ideally between 10.5 and 11.0)			
Slum flow ≥ 65 cm		The same SCC as for upstream containment wall was used, but without any constraint for the period of use.	
Period of use ≥ 2 h			Period of use ≥ 2 h
Max. temperature ≤ 50 °C			Max. temperature ≤ 50 °C
$f_c(28d) \geq$ 30MPa $f_c(90d) \geq$ 40MPa			$f_c(28d) \geq$ 25 MPa $f_c(90d) \geq$ 35MPa
Shrinkage (90d) ≤ 350 µm/m			Shrinkage (90d) ≤ 350 µm/m
Pumpable	Pumpable		Sprayable

Table 1 Requirements for self-compacting concrete and shotcrete used to build the containment walls

2.3 Bentonite admixture requirements

The initial bentonite admixture requirements were:

- To use a pure Wyoming sodium bentonite (Montmorillonite) such as MX80 or WH2;
- To make a granular admixture constituted for example by pellets and bentonite powder to fill the voids between the pellets;
- To construct the core with an industrial method which could be used underground at a depth of 500 meters;
- To verify the results with measurement means compatible with the underground localization of Cigéo (those means had to be qualified).

The final requirements on the bentonite core, even if no full scale hydration[1] was realized, were:

- Hydration swelling pressure expected above 4[2] MPa;
- Permeability after saturation ≤ 10^{-11} m/s.

3. Methods used to develop the seal components

3.1 General methods

All the methods used to develop the various seal components were empirical methods based on a progressive approach to reach the expected results.

3.1 Low pH concrete and shotcrete formulations developments

Here is the list of the different main steps of the global method used to determine the best compositions of a low pH SCC:

- Bibliographical analysis to investigate the different solutions used over the world (Finland, Spain, Switzerland, Sweden …) to decrease the pH value of concrete.
- Test of different binders (binary and ternary bends) to find the most appropriate composition to decrease the pH: 4 binders were selected.
- Determine with the software "BétonLab Pro 3" the different possible compositions regarding the availability of local materials: cement, aggregates, sand.
- Test in laboratory to determine the most promising compositions in batches of 30 liters.
- Verify the rheology of theses compositions after 2 hours (visual examination, slump flow test, and sieve segregation test).
- Determination of the values of different parameters (hydration temperature, pH, porosity, compressive strength… after 28 and 90 days).
- Improvement, step by step, of the results (3 iterations and around 300 SCC mixes were virtually studied) to determine the 3 best compositions to be practically tested in industrial-like conditions.

[1] Test of hydration was made at very small scale (a few liters cell) during FSS experiment and later in the REM experiment with an approximate volume of one cubic meter.

[2] At the beginning the value used to design the admixture was 7MPa; but as the result was not obtained during the metric tests, Andra decided for the final emplacement to specify 4 MPa. However all the initial conception of the admixture was made with an objective of 7 MPa.

Compound (kg/m^3)	B50 CEM I 52,5 Le Teil (100% nano-silica)	B50 CEM III/A 42,5 Héming (100% silica fume)	B50 CEM III/A 52,5 Rombas (100% silica fume)
Gravel 5/12 (dry)	807,7	737,8	682,1
Sand 0/4 (dry)	531,2	457,7	487,0
Sable 0/2 (dry)	230,9	198,9	211,7
Cement	108,0	132,0	130,0
Silica fume	0,0	132,0	130,0
Nano-silica Slurry	216,0	0,0	0,0
Limestone filler	335,5	396,9	408,4
Glenium Sky 537	≈ 8,0%	≈ 2,0%	≈ 2,2%
Prelom 510	0%	≈ 0,3%	≈ 0,3%
Water	70,2	205,7	204,1

Table 2 Identification of compositions to test in industrial conditions

- Test of these compositions to determine the different values of the principal requirements.
- The composition with nano-silica was not successful because the concrete began to harden too early (less than 2 hours). Another formulation using the same components but with silica fume instead of nano-silica was finally tested.
- After a new analysis of the different results, the choice was made to use the "Rombas composition".
- This formulation was then tested in a larger quantity (12 m^3) to see the scale effects before final emplacement.

For the shotcrete the analysis was similar but we did not test a larger quantity as we did for SCC (this wall certainly a mistake).

3.2 Bentonite admixture development

For the development of the bentonite admixture, the problem was not the same as for SCC or shotcrete because the only problem was to reach a dry density around 1.62 g/cm^3 permitting to obtain a hydration pressure of 7 MPa. Two subjects were studied:

- How to have the best dry density for each of the components?
- How to emplace these components in the most homogeneous possible way and with the smallest possible voids between them?

For the first subject, as the swelling material was imposed (pure sodic bentonite) and the use of granulate components was also imposed, all the investigation was to find how to obtain the highest possible dry density of the admixture components.

First, the investigation was on the pellets production machine because the pellets which form around 70% of the total volume had to have the highest possible density. The machine developed permitted to have a pellet dry density around 2.04 g/cm^3.

With that result for the pellets we began different laboratory tests to see how to elaborate the final admixture (test with 2 or 3 different components). The best result was obtained by combining 32 mm pellets with a powder (made of crushed pellets) used to fill the voids between the pellets.

In the laboratory with this admixture we effectively reached the expected dry density of 1.62 g/cm^3 while pouring the 2 components separately (first the pellets and then the powder).

Testing this solution inside a mock-up of a few cubic meters (a metric size concrete pipe) we noticed that what was possible in a laboratory could not be fully transposed. After several tests we could not obtain more than 1.52 g/ cm^3. So the newly specified dry density was revised down to 1.5 g/cm^3 in accordance with the metric test results.

4. Results

4.1. Low pH self-compacting concrete and shotcrete results

For the low pH SCC, the result was at the level of the different preliminary tests and the emplacement of the upstream containment wall was quite successful.

For the low pH shotcrete, the result was not at the level expected: hydration temperature was too high (67°C instead of less than 50°C) and a lot of cracks in the downstream containment wall were noticed.

4.2. Bentonite core results

During the first part of the filling operations (2/3 of the total volume composed by all the lower part of the mock-up and first part of the top) the dry density measured was better than expected (1.58 g/cm^3), but in the second part (end of the top of the drift model) the result was lower than expected (1.28 g/cm^3) for a global result which didn't reach totally the expected requirements (1.48 g/cm^3 instead of 1.5 g/cm^3).

5. Discussion

It's always possible to be satisfied or not by the FSS experiment outcomes; it depends of what was your own objective; and this objective is not obligatory the same for all people working on the subject: it depends of their sensitivity… For example is the 1.48 g/cm^3 density value a bad result when at the beginning your requirement was 1.62 g/cm3 and finally you opted for a theoretical value of 1.5 g/cm^3? To answer this question it is necessary to take a little height and consider there is room for improvements!

In the case of FSS a few people were not satisfied of the results because all the requirements were not totally fulfilled… It's very often in the case of difficulties that you learn the most part and that you can also provide improvement solutions for your future tests.

6. Conclusions

Globally for Andra FSS was a technical success because this experiment showed the feasibility of emplacing great quantities of low pH self-compacting concrete, shotcrete ant bentonite admixture… which was its main objective; but different ameliorations could have been done, and will have to be taken into account in the future conception, to reach in totality the expected requirements in terms of shotcrete use (if it is used) and naturally bentonitic material which is the main component of the seal.

7. Acknowledgements

We should like to acknowledge the Consortium in charge of the construction of the construction of the test drift and its filling (EIFFAGE TP, CEA/LECBA, LAVIOSA and SOLEXPERTS) which did with their own subcontractors a positive work, as well as the different other contracted companies in charge of the safety, the quality and the technical assistance to Andra.

Andra also acknowledges the EC financial support of its FSS related activities within the DOPAS project (EC Contract Agreement 323273).

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8.1. Concrete and shotcrete

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- FSS-1 : Bétons bas pH autoplaçants : bilan des études de laboratoire « CG-TE-F-NTE-CFS1-GC0-4000-13-4044/A »
- FSS-1 : Bétons bas pH autoplaçants : bilan des essais à l'échelle industrielle « CG-TE-F-NTE-CFS1-GC0-4000-13-4045/A »
- FSS-1 : Rapport final remplissage du massif amont en béton bas pH : « CG-TE-F-NTE-CFS1-GC0-4000-13-0039/A »
- FSS-1 : Bétons bas pH projetés : bilan des études de laboratoire « CG-TE-F-NTE-CFS1-GC0-4000-13-4046/A »
- FSS-1 : Bétons bas pH projetés: bilan des essais à l'échelle industrielle « CG-TE-F-NTE-CFS1-GC0-4000-13-4047/A »
- FSS-1 : Rapport final remplissage du massif aval en béton projeté bas pH : « CG-TE-F-NTE-CFS1-GC0-4000-14-0007/A »

8.2. Bentonite

- FSS-1 : Conception des matériaux à base d'argile gonflante « CG-TE-F-NTE-CFS1-GC0-4000-12-4000/B »
- FSS-1 : Rapport final réalisation du noyau de bentonite « CG-TE-F-NTE-CFS1-GC0-4000-14-0005/A »

DOMPLU - filter and seal design, construction and results (DOPAS Project)

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The deposition tunnels in a KBS-3V repository for spent nuclear fuel will be sealed with a plug at the end of the tunnels in order to withstand the swelling of the backfill and to seal off out-flowing groundwater. A full scale test of the dome plug system (The DOMPLU test) is currently performed at the Äspö Hard Rock laboratory (HRL) in a joint project between SKB and Posiva. The full-scale test consists of a number of components: bentonite backfill and seal (both blocks and pellets) and filters (Leca beams and gravel). These components are instrumented with sensors for measurement of total pressure, pore pressure, relative humidity and displacements at several positions. The bentonite-based components and the filter were installed in January 2013 and pressurization by natural groundwater inflow began in October 2013. The installation was preceded by a blind prediction of the evolution of hydro-mechanical processes using a finite element model (Code_Bright). Sensor data have been analyzed together with calculated evolutions of RH, stresses and displacements.

1 Background

The deposition tunnels in a planned repository for spent nuclear fuel will be sealed with a plug at the end of the tunnels in order to withstand the swelling of the backfill and to seal off out-flowing groundwater. The principle design of the plug includes several components, among which the most important are the concrete dome, the bentonite seal and the filter (Figure 1). The groundwater leakage past the plug has to be small enough in order to build up a water pressure inside the plugged volume, and to prevent loss of bentonite from the deposition holes due to erosion throughout the operational phase of the repository. During construction of the plug system and while the concrete dome cures until it is finally grouted for a tight contact to rock (a total period of 4 to 5 months) the construction site must be kept free from water. Wet tunnels therefore require a filter section which can drain the water coming from the inner parts of the tunnel and temporarily let it by-pass the plug. These issues and demands have been addressed in the joint SKB and Posiva project “System design of dome plug for deposition tunnels”. The project aims to ensure that the reference configuration of the KBS-3V deposition tunnel end plug works as intended, and includes a recognized need for demonstration of plug performances. The project included verification of the modified dome plug design by analytical and numerical calculations, laboratory examinations of all plug component materials and several scale tests (Börgesson et al. 2015). The main activity though, was to test the dome plug system in full scale (The DOMPLU test) at the Äspö Hard Rock laboratory (HRL). The rock conditions at Äspö HRL are not as good as found in Forsmark, the site for the Swedish Spent Fuel Repository, but nevertheless the experiment could be carried out at similar depth (450 m) in crystalline rock with comparable overburden pressure.

2 Design

The full-scale test consists of a number of components, each with its own purpose (Figure 1). The innermost component is a 1 m backfill zone which consists of a stack of bentonite blocks with a surrounding pellet filling. The next component is the filter section which is composed of 0.3 m thick LECA-beams and a 0.3 m layer of gravel (2-4 mm). The filter serves for drainage of groundwater during construction as well as for artificial wetting of the bentonite seal when the drainage is finally closed. The gravel and the bentonite seal are separated by a geo-textile which also facilitates distribution of water into the sealing. The bentonite seal consists of a 0.5 m stack of highly compacted MX-80 bentonite blocks with a surrounding MX-80 pellet filling closest to the rock. Finally, the restraining concrete structure is designed as an octagonal dome plug, cast in-situ by low-pH concrete. The diameter of the concrete dome is 8.8 m while the concrete thickness is 1.79 m in the hub. The design load for the desirable watertight structure is 7 MPa and the water flux past the plug will be restricted to a maximum of 0.1 l/min.

3 Installation

Besides extensive monitoring of the concrete dome structure, the inner plug components are instrumented with sensors for measurement of total pressure, pore pressure, relative humidity and displacements at several positions. The bentonite-based components and the filter were installed in January 2013 (Figure 2) while the concrete dome was cast in March 2013 (Grahm et al. 2015). Pressurization by natural groundwater inflow began in October 2013 (day 243). The artificial pressurization was increased to 4 MPa, stepwise during the period from December 2013 to February 2014, and has been maintained at this level after that. The measured leakage past the plug on September 17, 2014 was 44 ml/min (day 595, blue line Figure 3). One year later, this was only marginally lower (approximately 20-30 ml/min). Monitoring of DOMPLU will continue until late 2016.

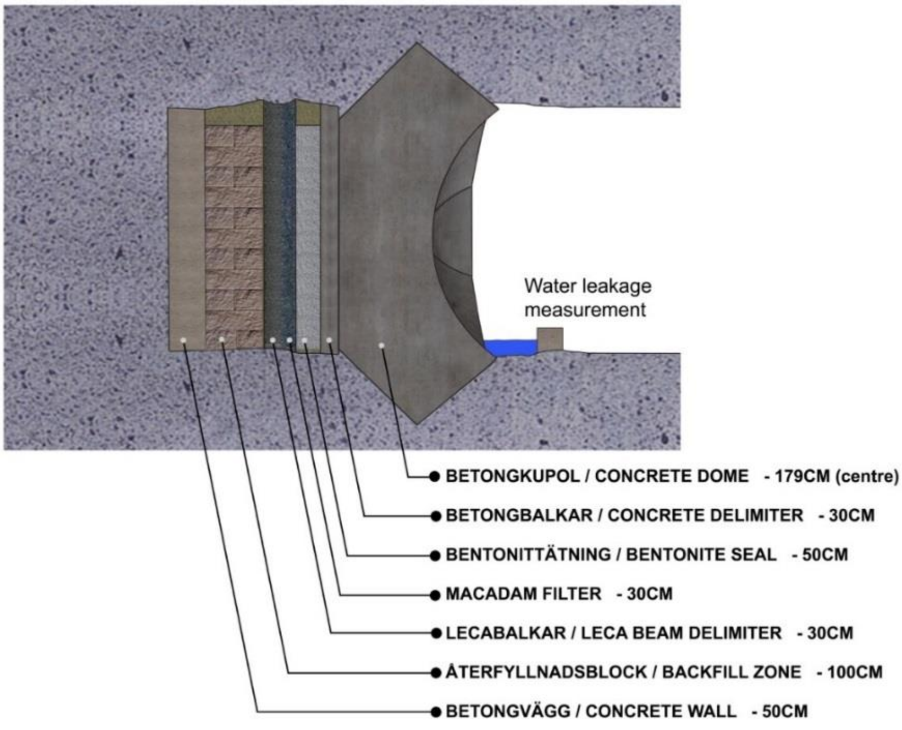

Figure 1. Schematic section of DOMPLU.

Figure 2. Installation of backfill blocks behind Leca beams (left) and seal blocks behind concrete beams (right).

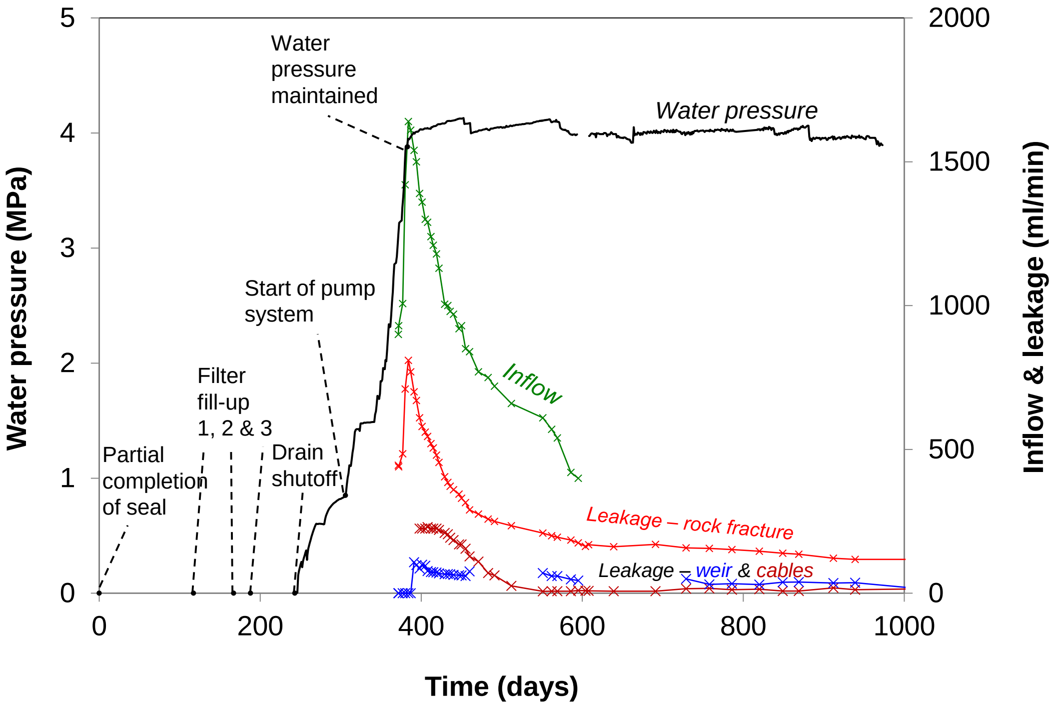

Figure 3. Timeline of major events, water inflow, measured leakage and water pressure.

4 Predictions

A blind prediction of the evolution of hydro-mechanical processes in the full-scale test was performed with a 2D axisymmetric Code_Bright model prior to the installation. This model included representation of bentonite backfill and seal (both blocks and pellets) as well as filter materials (Leca beams and macadam), see Figure 4. The mechanical processes of the bentonite-based materials were modelled with the thermoelastoplastic constitutive laws, based on the Barcelona Basic Model (BBM). The adoption of the mechanical parameter values followed the same strategy as for the data report for SR-Site (Åkesson et al, 2010). All materials were modelled with an initial suction and the build-up of stresses were driven by the bentonite hydration. Water was supplied through surface boundary defined in the pellets and filter materials. Details on the model is given by Börgesson et al. 2015.

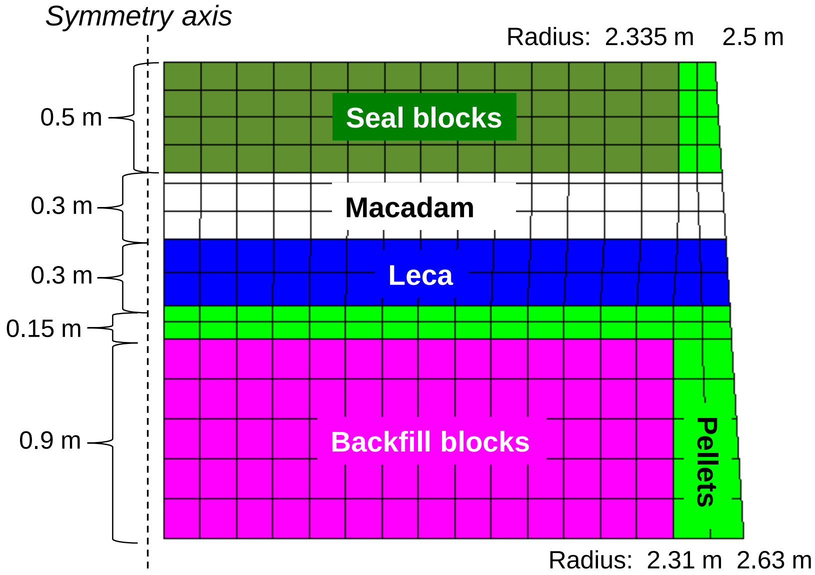

Figure 4. Numerical model: geometry and mesh.

5 Results

Measured and calculated evolutions of RH, axial stresses and displacements at different positions are shown in Figure 5. For the numerical prediction, it was assumed that the filter would be filled with water immediately after installation, whereas this occurred after day 188 in the full-scale test. Nevertheless, the prediction of the early evolution showed a fairly good agreement with data from the RH sensors, and an explanation for this may be that the bentonite had access to some groundwater before the filling of the filter. Still, the measure increase in RH was generally more rapid than the predicted evolution after the filling of the filter, and an explanation for this may be an effect of the pressurization. Predicted stresses and displacements, on the other hand, showed a more rapid evolution than the corresponding data from the full-scale test, especially before the water filling of the filter. The reason for this may be that the gaps between the blocks, which were not represented in the model, had to be closed before any stresses could build up. The general magnitude of the predicted displacements were fairly accurate, especially concerning the still functioning sensor at the interface between the Leca beams and the pellets-filled slot.

6 Concluding remarks

Results from the full-scale test, both sensors data and leakage measurements, show together with the numerical prediction that the plug components have functioned as intended. This concerns both the drainage capacity of the filter and sealing ability of the bentonite seal, although the concrete dome probably also has a significant sealing ability. It should be noted that the reduction of the leakage during the last year was fairly marginal. The pellet-filled slot behind the filter also appears to have reduced the build-up of stresses as intended.

7 Acknowledgements

The research leading to these results has received funding from the European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013 under grant agreement no 323273, the DOPAS project.

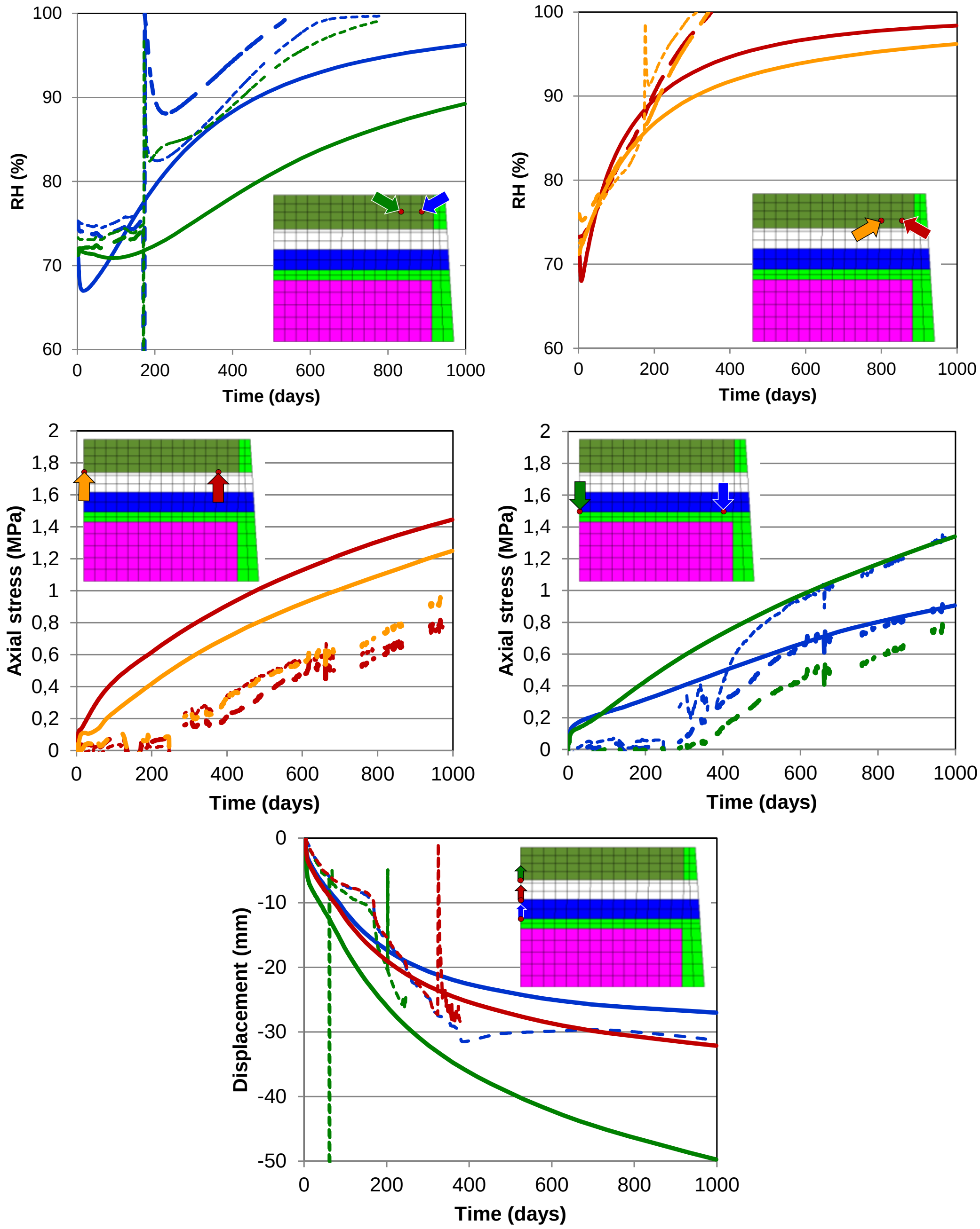

Figure 5. Evolution of relative humidity (upper), axial stresses (centre, evaluated as total pressure - water pressure) and axial displacements (lower). Model (solid lines) and experimental results (dashed lines). Sensor location indicated with arrows in figure with same color as lines.

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Bentonite-based materials for the Full-Scale Emplacement (FE) experiment: design and production steps

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The Full-Scale Emplacement (FE) experiment at the Mont Terri underground rock laboratory (URL) is a full-scale multiple heater test in Opalinus Clay (Figure 1). According to the Swiss disposal concept, it simulates the construction, waste emplacement, backfilling and early post-closure evolution of a spent fuel (SF) / vitrified high-level waste (HLW) emplacement tunnel as realistically as possible. A granulated bentonite mixture (GBM) and highly compacted bentonite blocks were used to backfill the FE tunnel. The raw bentonite material and the production of the GBM were contracted by public tendering according to World Trade Organization standards (Garitte et al., 2015). Approx. 350 tons of raw bentonite (National ® Standard WP2) were transformed into a GBM. The aim of the GBM production process is to increase the loosely poured bulk dry density of the raw bentonite material, which is approx. 1.0 g/cm^3, to an emplacement dry density of 1.45 g/cm^3 based on correlations observed between the emplacement dry density and other key parameters such as the hydraulic conductivity, the swelling pressure and the thermal conductivity. A minimum dry density of 1.45 g/cm^3 was also found to be a threshold for microbiological activity (Stroes-Gascoyne, 2011). In the FE experiment, the heaters were placed on top of compacted bentonite block pedestals. A 2 m long section of the interjacent sealing section was backfilled with compacted bentonite blocks (sealing sections in emplacement tunnels have been proposed as an option for the Swiss concept, replacing every tenth canister, with steel arch rock support instead of shotcrete rock support (Nagra 2010)). The production of 2500 rectangular and 500 curved "top layer" blocks (approx. 70 tons in total) is described in the second section.

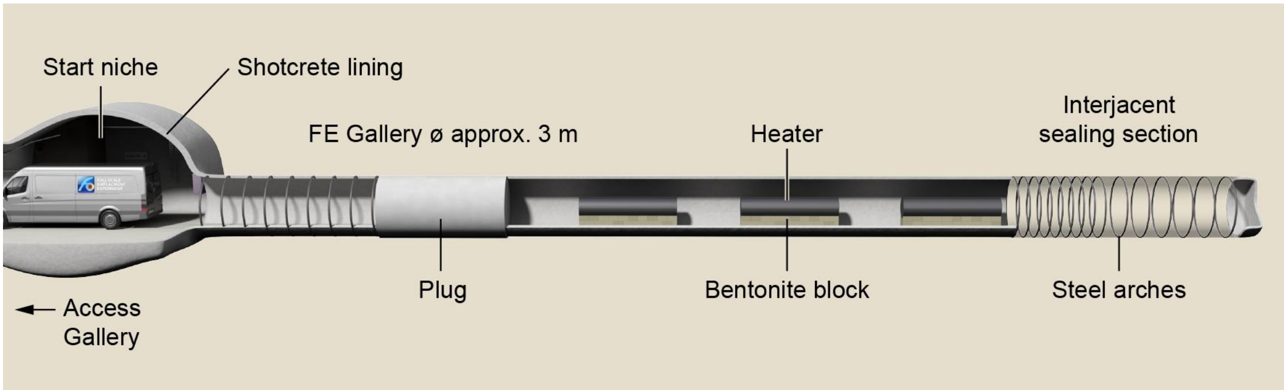

Figure 1: Visualisation of the FE/LUCOEX experiment at the Mont Terri URL representing a section of the repository tunnel (backfill not shown).

1 Granulated bentonite mixture (GBM): design and production steps of a self-compacting material

Blümling & Adams (2008) presented a summary of the work carried out on the use of bentonite pellets as a backfill material as part of the borehole sealing project within the context of the Phase IV (1994 – 1996) research and development activities at the Grimsel Test Site, in collaboration with the Agence Nationale pour la gestion des déchets radioactifs (Andra). The authors showed systematically that the emplacement dry density is dependent on:

- The dry density of individual pellets
- The grain size distribution of the pellets
- The particle shape of the pellets
- The emplacement method

The different issues raised by Blümling & Adams were further investigated in a series of experiments (e.g. Kennedy et al., 2003; Plötze & Weber, 2007).

The design basis for the production of the FE backfill material is discussed based on work by previous authors. Practical lessons from the FE GBM production are then summarised, focusing on:

- The pelletization method and pre-treatment of the raw material required for achieving high quality compaction
- Mixing method for obtaining a broad grain size distribution and hence a self-compacting mixture that will reach a high emplacement density

The production of a bentonite pellet mixture includes several processing steps (Hoffmann et al., 2007). The raw material is generally provided at a gravimetric water content of about 10 – 15 %. It is dried by heating to obtain a lower water content in the range of 3 – 6 %, close to Proctor's optimum, enabling a higher pellet dry density after compaction. The maximum temperature to which the raw bentonite may be exposed during the drying process was determined for this project to be 80 °C. Considering the upper temperature limit of only 80 °C, the efficiency of the drying process depends on the grain size distribution of the raw bentonite material and the residence time in the heating chamber. Maintaining a reasonable production rate of 1.5 tons/hour, the water content of the FE bentonite could be decreased to 4 – 6 %.

The aim during the pelletizing process is to increase the pellet dry density, i.e. to reduce the intra-pellet porosity. For the FE experiment, the pellets were produced by compaction between flat rollers (resulting in flat pellets of irregular shape). Although alternative methods exist (see Pietsch, 2005), this method was found to be favourable from an economical point of view with a reasonable production rate (1 to 2 tons per hour). However with this method the maximum grain size of the pellets was 8 millimetres instead of 15 millimetre diameter that was targeted. The pellet shape was elongated.

The bentonite pellets produced were then mixed in a Kniele mixer, providing enough energy input to break some of the pellets and produce a mixture with broad grain size distribution with the aim of reducing the inter-pellet porosity by filling larger pores between large particles with smaller particles at all scales between zero and the maximum grain size. A specific mixing cycle, including high energy mixing of pellets only in the first phase and smooth mixing after addition of 20 % of raw material in a second phase, was designed to obtain a grain size distribution close to a Fuller type distribution (illustrated in

Figure 2; Fuller & Thompson, 1907). The mixture production rate was approximately 2 tons/hour.

Figure 2: Photo of the granulated bentonite mixture (GBM) produced for the FE experiment.

Intensive testing of the pelletizing and mixing processes resulted in 4 main mixture types. The influence of pellet dry density and grain size distribution are illustrated in Figure 3 where the pouring dry density of the 4 different mixtures is compared. As the mixture density depends on the measurement method, a measurement protocol was designed to compare the mixture dry density during production. Nevertheless, the presented values should not been interpreted in absolute terms. The FE tunnel was filled exclusively with mixture 3 (heated section) and mixture 1 (interjacent sealing section and section close to plug).

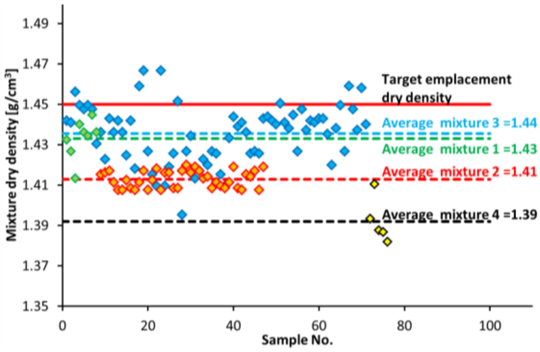

Figure 3: Comparison of the pouring dry density for FE mixture 1 (green dots), 2 (red dots), 3 (blue dots) and 4 (yellow dots), measured every 2 tons during production.
Mixtures 1 and 3 are characterised by a similar grain size distribution and a similar pellet dry density. Mixtures 3 and 4 are characterised by a similar grain size distribution but the pellet dry density of mixture 3 is approx. 10 % higher than that of mixture 4. Mixtures 1 and 2 are characterised by a similar pellet dry density but mixture 2 is lacking a small amount of fine material and thus deviates from the optimum Fuller curve.

Some of the pellets disintegrate during the mixing process, which results in a loss of pellet dry density. This loss was confirmed by measuring the pellet dry density of different size classes sieved out of the granulated bentonite mixture (Figure 4). Apparently large particles do not suffer density degradation, whereas smaller pellets (that were obtained as a result of splitting larger particles) have a pellet dry density loss of approx. 10 %.

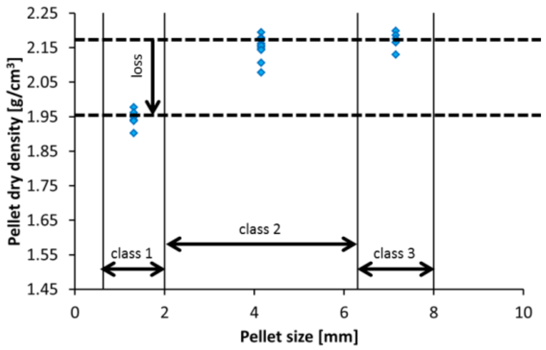

Figure 4: Pellet dry density measured on material sieved out from mixture 3 at ETH using a GeoPyc for three different sizes of pellets (1: between 0.63 mm and 2 mm; 2: between 2 mm and 6.3 mm and 3: between 6.3 mm and 8 mm).
10 measurements for class 1 and 2 and 5 measurements for class 3.

The production of the GBM in four process steps resulted in a satisfactory end-product. A clear and simple recipe (Mixture 3) was designed for a GBM at industrial scale that lead to an emplacement dry density of approx. 1.5 g/cm^3 in the FE tunnel. Potential for further compaction was identified. The material is also robust in terms of storage and handling steps. The initial requirements had to be slightly modified for practical reasons during production (maximum grain size of the pellets was smaller than desired and the mixture characteristics had to be optimised; final mixture characteristics were within requirements). The procedure was defined on the basis of an extended analysis of existing literature. The main control parameters (water content, pellet dry density, grain size distribution of the mixture) were shown to have a low variation, favouring homogeneous emplacement.

2 Compacted bentonite blocks: design and production steps for a highly compacted robust material

A total number of 3000 blocks was required to install 3 block pedestals for the heaters and to backfill 2 metres of the FE experiment tunnel (block mass was approx. 25 kg).

For the FE block production, the recommendations made in SKB (2010) summarising the efforts made since the first industrial production (Johannesson, 1999) were followed. According to previous bentonite block productions, the quality and strength of bentonite blocks depends on:

- (i) The compaction method (isotropic/isostatic or oedometric/uniaxial compression)
- (ii) The compaction pressure, pressing time and pressing cycle
- (iii) The initial water content of the raw material
- (iv) The grain size distribution of the raw material
- (v) The type (mineralogy) of the raw material (Na or Ca bentonite)

Two pre-productions were performed to investigate issues related to items ii, iii and v. The sensitivity of compacted bentonite blocks to ambient relative humidity was investigated thoroughly and systematically to optimise the manufacturing parameters (items ii and iii) and to avoid damage to the blocks during in-situ emplacement operations (Garitte et al., 2015).

Four groups of two blocks with different initial conditions were emplaced at the Grimsel Test Site (GTS) and monitored via a dedicated webcam observation system. The experiment was installed on 19.09.2013 (RH at that time = 70 %). The blocks were loaded with pressure induced by a heater on the bentonite blocks in the FE experiment.

The test was set up to verify previous laboratory test results and to investigate phenomenologically the mechanisms behind those results. Blocks compacted at a low water content disintegrated very quickly, the support capability was lost within only one month and the first significant fractures appeared in the first days after emplacement (Figure 5). Video cameras placed in front of the blocks and recording a picture every minute allowed monitoring the block disintegration behaviour.

In the low water content blocks, the first fractures appeared within the first hours. The videos (see QR codes in Figure 5) clearly showed the link between fracture development and swelling behaviour. The swelling, caused by water absorption by the relatively dry bentonite from relatively wet air, generated cracks that propagated very quickly. The relatively wet air penetrates into the fractures and expands the fracture inside the block. Drying cracks were also observed in the blocks equilibrated at 35 % air humidity (RH) in the laboratory tests, but these were shrinkage cracks and did not penetrate into the blocks. Blocks produced at a higher water content and thus characterised by a higher equilibrium RH took up almost no water and proved to be very stable over a long time period of approx. 1.5 years.

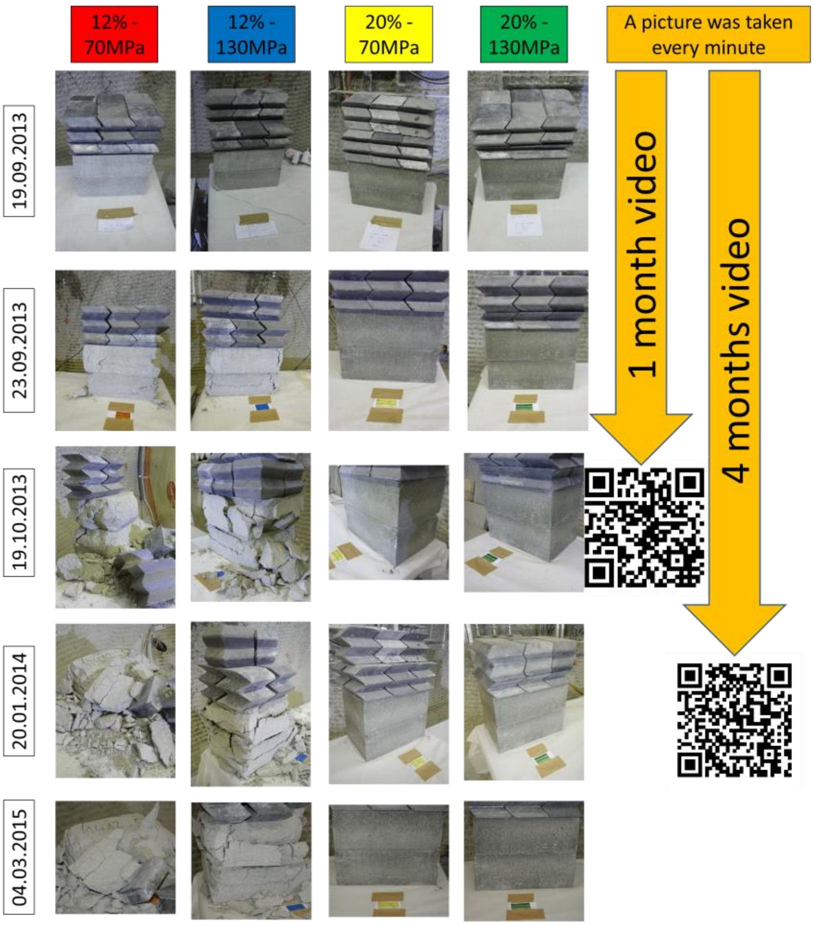

Figure 5: Behaviour of compacted bentonite blocks exposed to a relative humidity varying between 60 % and 85 % for different production parameters (water content and compaction pressure are indicated at the top of the figure).
The QR codes are linked to time-lapse videos of the block evolution.

For the FE bentonite block production, an average block dry density of 1.78 g/cm^3 was achieved. All other requirements, selected according to the state of the art and the pre-tests performed in the FE experiment (geometry variable, strength, density and water content), were checked for each block during production and were found to be fulfilled and very stable over the production time (Figure 6).

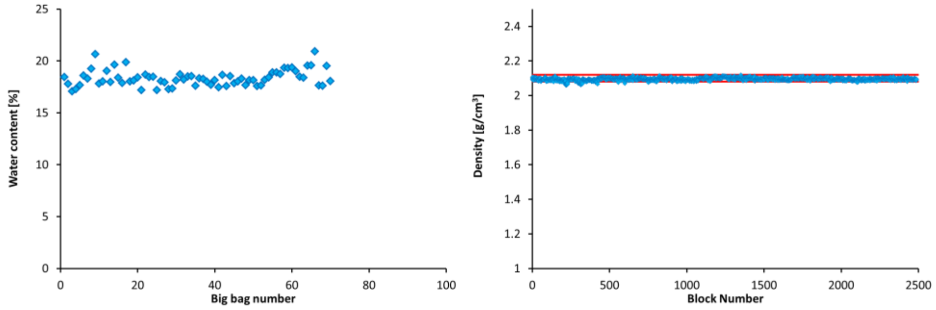

Figure 6: Water content of the raw material after homogeneous wetting (left figure) and block density measured on every block during the production (right figure).

The achieved dry density is a result of the adjustment of the water content of the raw bentonite material and of the compaction pressure to produce bentonite blocks that are as stable as possible with respect to changing climatic conditions in the emplacement tunnel. A higher dry density is possible, but with a loss of resistance to climatic conditions as a consequence. Each compacted bentonite is characterized by an equilibrium RH. Its value depends on the water content and the compaction pressure. A bentonite block is stable as long as ambient air relative humidity does not exceed its equilibrium relative humidity by more than 5 % to 10 %. With the equilibrium RH concept in mind and taking extreme care with packaging, the experience acquired in the FE experiment shows that it is possible to store compacted bentonite blocks for a full year (or longer) without compromising key requirements. Nevertheless, the tests suggested that it might be impossible to produce blocks with an equilibrium RH higher than 70 %. If the ambient RH at the repository site is higher than 80 %, this might result in practical problems during the emplacement activities, but there are technical possibilities for drying the air in the emplacement tunnel.

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Acknowledgement

The engineering and demonstration components of the FE Experiment are also part of Nagra's participation in the EU project 'Large Underground COncept Experiments' (LUCOEX). The LUCOEX project has received funding from the European Union's EUROATOM research program (FP7) under grant agreement 269905.

Nagra thanks the European Union for supporting this work. Nagra also thanks the LUCOEX partners ANDRA (France), POSIVA (Finland) and SKB (Sweden) for the continuous discussion and knowledge exchange throughout this EU project and beyond.

Horizontal bentonite backfilling and concrete plug for the Full-Scale Emplacement (FE) Experiment at the Mont Terri URL: requirements, design, instrumentation and emplacement

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The Full-Scale Emplacement (FE) Experiment at the Mont Terri underground rock laboratory (URL) is a full-scale multiple heater test in Opalinus Clay. According to the Swiss disposal concept, it simulates the construction, waste emplacement, backfilling and early post-closure evolution of a spent fuel (SF) / vitrified high-level waste (HLW) emplacement tunnel as realistically as possible. The main aim of the experiment was to investigate repository-induced thermo-hydro-mechanical (THM) coupled effects on the host rock at this scale and to validate existing coupled THM models. The construction of the 50 m long experiment tunnel with a diameter of approx. 3 m was completed in September 2012. The backfilling of the FE tunnel, Figure 1, was carried out between July 2014 (emplacement of a porous concrete plug at the back end of the tunnel) and March 2015 (closure of the experimental section with a concrete plug).

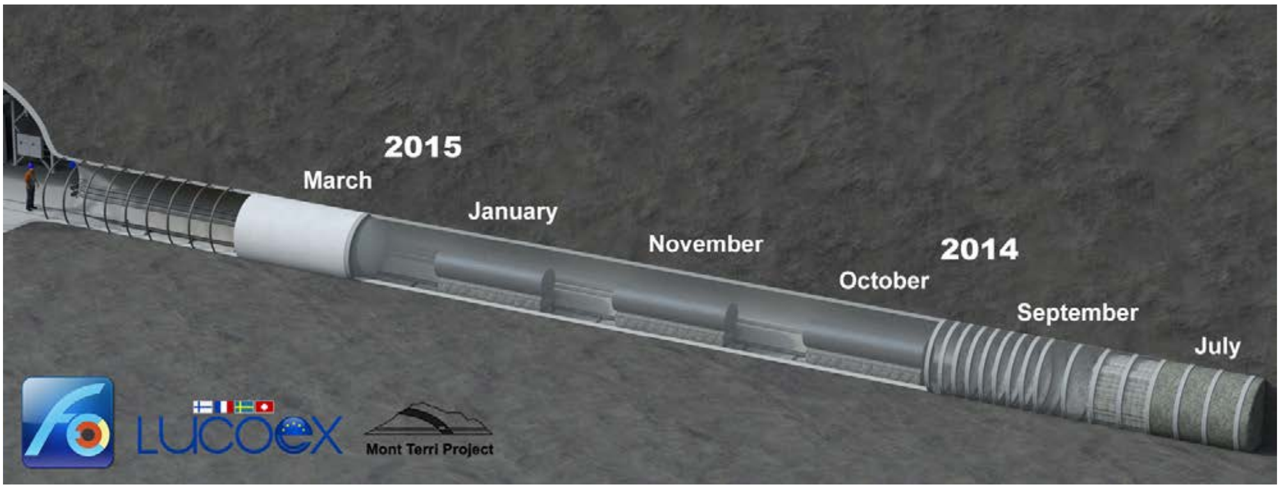

Figure 1: Visualisation of the FE/LUCOEX experiment at the Mont Terri URL (backfill not shown)

In the FE tunnel, three heaters with dimensions similar to those of waste canisters were emplaced on top of pedestals built of bentonite blocks between October 2014 and January 2015. The remaining space was backfilled with a granulated bentonite mixture (GBM) using a prototype machine with 5 screw conveyors developed for this purpose. The main requirement related to the emplacement dry density. Based on correlations observed between the emplacement dry density and other key parameters such as the hydraulic conductivity, the swelling pressure and the thermal conductivity, a minimum dry density of 1.45 t/m^3 was targeted. This was also found to be the threshold for microbiological activity (Stroes-Gascoyne, 2011). Finally, in February and March 2015, the experiment was sealed off with a 5 m long concrete plug holding the bentonite buffer in place and reducing air and water fluxes. The paper describes the quality control of the dry density during the horizontal emplacement procedure for underground conditions and the design and construction of the friction plug emplaced to close the experimental section. The FE plug has no demonstration character, but the lessons learned have relevance for the design and construction of future repository plugs, as well as for other experimental plugs.

Horizontal backfilling

The range of possibilities for backfill materials was assessed for the FE Experiment. After selecting natural sodium bentonite from Wyoming and several parameter optimisation tests, approx. 350 tons of a granulated bentonite mixture (GBM) were produced in Germany. The GBM consisted of highly compacted bentonite granules with an average particle dry density of 2.18 t/m^3. After production by roller presses, the granules were mixed and sieved to achieve a very broad grain size distribution, a so-called Fuller-type distribution. The production processes are described in a companion paper (Garitte et al., 2016) and in Garitte et al. (2015).

Based on experience from preceding projects and on extensive pre-testing (Köhler et al., 2015), a prototype backfilling machine was designed and manufactured (Figure 2). This machine transports, emplaces and compresses the granulated bentonite mixture in horizontal small-diameter tunnels as densely and homogeneously as possible using five screw conveyors, without applying additional compaction. It was tested extensively in a surface industrial facility before using it underground in Mont Terri.

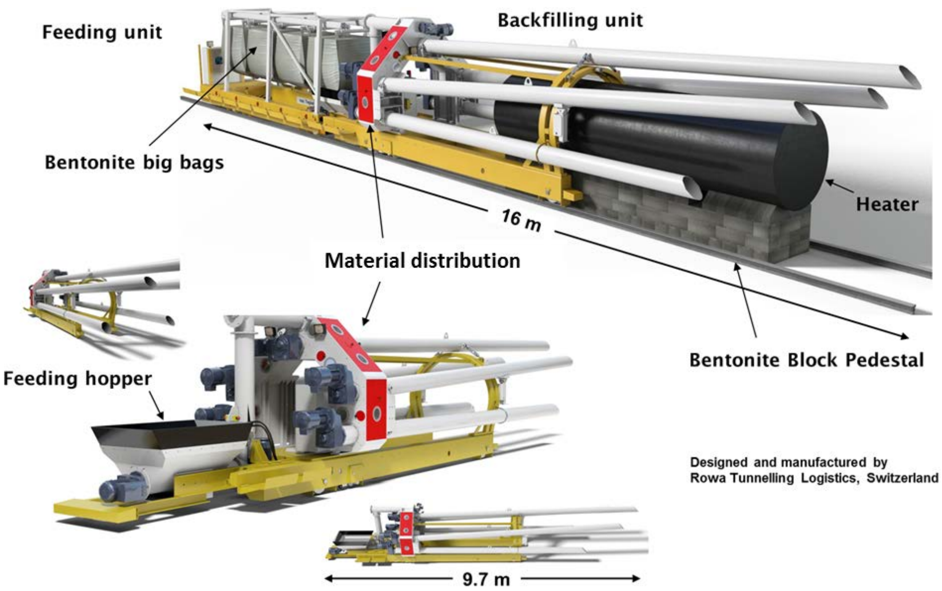

Figure 2: The backfilling machine for the FE Experiment

Mock-up tests were conducted to check and optimise the technology in a set-up representative for the conditions at Mont Terri. All relevant parameters, such as the backfilling speed and the backfilling pressure, were checked in the off-site tests. Process-related interfaces such as the geometries of other components (tunnel walls, bentonite pedestal and heater, sensors and cables, etc.) were also investigated (Figure 3).

Figure 3: Photo of the rear end of the backfilling machine ready to start backfilling the steel tunnel tube

The off-site tests offered the possibility to perform a detailed quality control (QC) of the backfill, which is not conceivable in an underground facility. Different methods for local density assessment such as slope laser scanning, dielectric tools, gamma-gamma logging and cone penetration testing were developed. The local dry density values derived from these methods range from 1.4 to 1.7 t/m^3. Generally, they show good consistency and allow the homogeneity of the emplacement to be characterised (Figure 4). This characterisation allowed a higher dry density zone in the area of the screw conveyor tips to be identified.

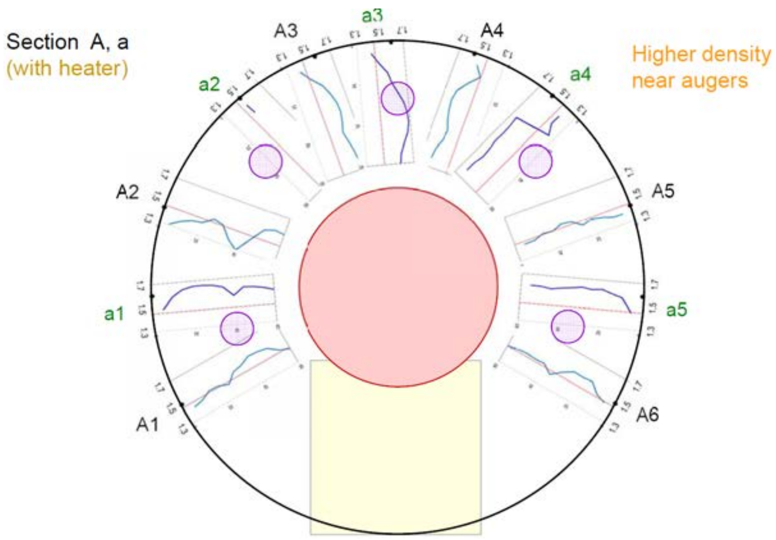

Figure 4: Dry density profiles derived from dielectric profile measurements around the dummy canister

Emplaced volume estimation was performed by geodetic laser scans of the slopes (Figure 5). Sectional values for dry density from mass-volume balance calculations were between 1.48 and 1.55 t/m^3 (Table 1). The off-site mock-up tests provided an opportunity to optimise the measurement methodology and to develop protocols for calculating the measurement error. The error calculation given in Table 1 is based on the following conservative assumptions:

- 0.35 % due to weighing inaccuracy and 2.5 kg material loss per bigbag of approx. 700 kg
- Standard deviation in water content measurements (5.54 ± 0.16 % for Mock-up 1 and 5.60 ± 0.09 % for Mock-up 2)
- Inaccuracy in volume estimation (1 % for Mock-up 1 and 0.2 % for Mock-up 2)
- Inaccuracy in positioning of the survey (± 0.01 m3)

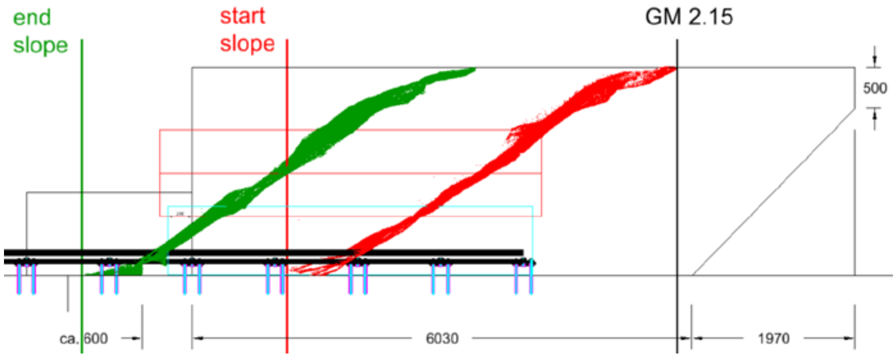

Figure 5: Slope scans for distinct volume estimation around the dummy canister and beyond

Table 1: Dry density results in [t/m3] calculated from mass-volume measurements

Values [t/m^3]	**Mock-up 1**	**Mock-up 2 gap**	**Mock-up 2 around canister**	**Mock-up 2 total**
Average dry density	1.498	1.490	1.525	1.502
Measurement error	± 0.023	± 0.013	± 0.022	±0.009

With the FE Experiment, it was possible to demonstrate that, using a GBM and a suitable backfilling machine, an overall bulk dry emplacement density of at least 1.45 t/m^3 (as targeted for this experiment) can be achieved in horizontal emplacement tunnels in Opalinus Clay. The overall dry density measured in the on-site test was 1.489 ± 0.003 t/m^3. Following the methodology developed off-site and using a 3D volume scan of the tunnel, the variation in the dry density along the tunnel axis was measured in 12 sections of the FE tunnel (Figure 6). The measured variation along the tunnel axis is relatively small and only volume no. 12 (close to the retaining wall) is characterised by a measured dry density significantly lower than the target value. Filling of this volume had to be performed in steps, whereby the lower screw conveyors of the backfilling machine were removed while the retaining wall was constructed. In sectional volumes 4 to 11, which can be considered representative of routine emplacement, the average dry density is 1.513 ± 0.003 t/m^3.

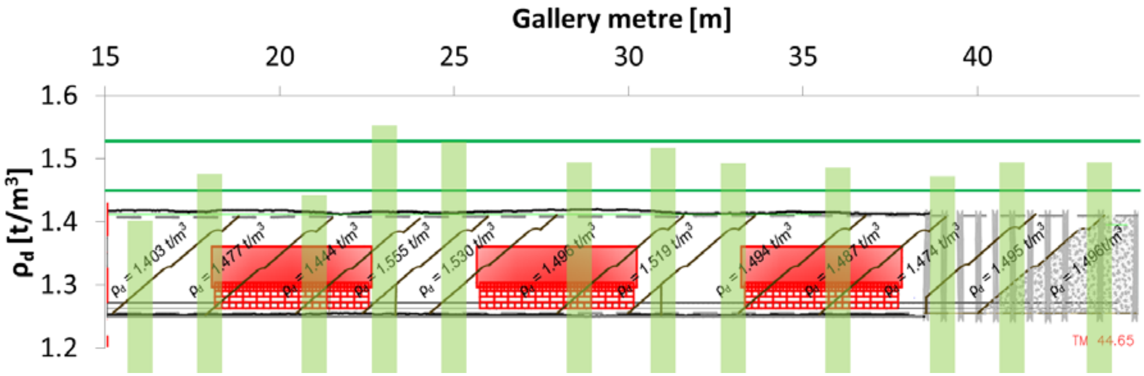

Figure 6: 12 sectional volumes along the FE tunnel axis in which the dry density was calculated from mass-volume measurements. Sectional volume 1 is at the back (right) end of the tunnel and Sectional volume 12 is at the front (left) end of the tunnel

Concrete plug

The FE plug was designed to withhold the potential swelling pressure of a fully saturated bentonite backfill of approx. 3.5 MPa for an average bulk dry density of about 1.45 t/m^3 and to limit water and air fluxes between the experimental zone and the open tunnel system. The plug design was aimed at limiting the fluxes through the concrete, at the interface between plug and shotcrete and through the EDZ (Q1, Q2 and Q3 in Figure 7), but also around the cable bundle (750 cables) that was routed through the plug.

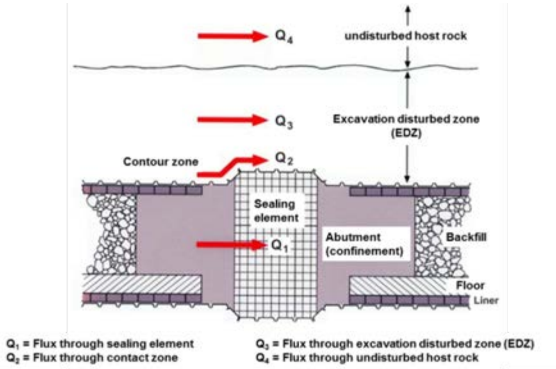

Figure 7: Potential fluxes through a sealed section. Note: in the FE experiment, the shotcrete lining was not removed because of the risk of destroying the instrumentation cables

The plug was designed as a friction-controlled plug. 50 steel dowels were installed radially through the rock - shotcrete - plug interface to increase the shear resistance at the concrete-shotcrete interface. Each of the dowel boreholes was injected with resin in order to seal the EDZ around the plug. Approx. 29 m^3 of self-compacting concrete were pumped into the space between the 20 cm thick retaining wall erected at tunnel metre (TM) 15 and the formwork placed at TM 9.8. In order to limit the curing temperature of the concrete to a maximum of 50°C, 60% of the Portland cement was replaced by fly ash and microsilica. 40 days after casting, the shrinkage gap at the plug / shotcrete interface was injected with resin with a pressure of approx. 5 bar to seal the interface. The theoretical estimation of the shrinkage gap was less than 1 mm (resulting from a measured concrete shrinkage of approx. 0.02%). However, although a highly flowable concrete was used, an air pocket remained at the top back end of the plug. This air pocket was clearly identified from the volume of resin injected to close the shrinkage gap and by continuous qualitative water content measurements through TDR cables installed around the tunnel wall perimeter.

The oxygen concentration monitored in the GBM backfill showed a rapid decrease (Figure 8). The oxygen sensors close to the retaining wall did not decrease to zero, differently to further distant sensors. The residual oxygen concentration in these sensors varied and this variation could be clearly correlated to atmospheric pressure variations in the entrance tunnel. Despite the fact that the plug was installed with the highest possible care to improve its sealing properties, a full disconnection could thus not be achieved. The most probable explanation is the difficulty of correctly sealing the 750 instrumentation cables routed through the plug.

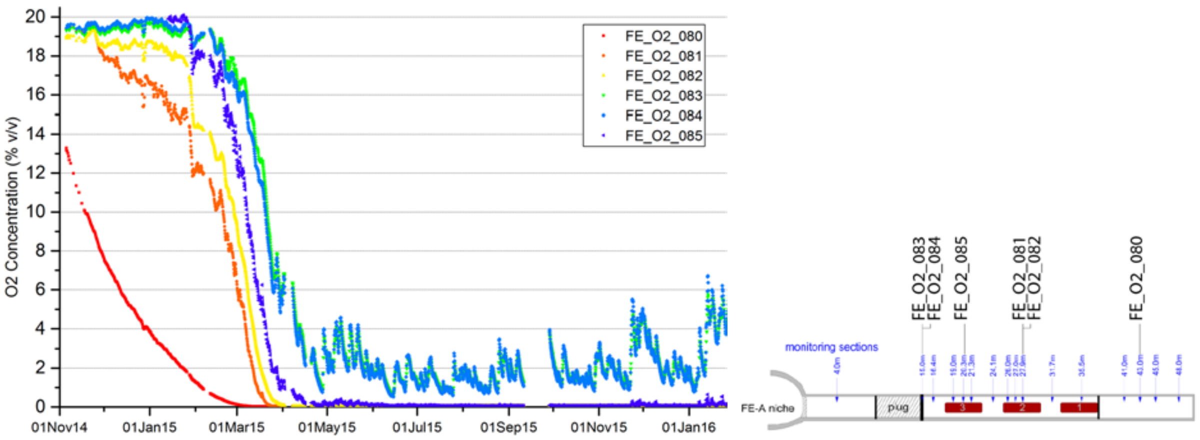

Figure 8: Oxygen concentration measured in the GBM backfill at several distances from the retaining wall

Acknowledgments

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Hydro-mechanical and chemical-hydraulic behaviour of different types of shaft sealing materials (DOPAS Project)

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This paper describes research and development work on plugging and sealing repositories, an issue of fundamental importance for the rock salt option which represents one of the three European repository options, besides the clay rock and the crystalline rock options. The programme aims at providing experimental data needed for the theoretical analysis of the long-term sealing capacity of concrete-based sealing materials, excavated claystone material and mixtures with bentonite. In order to demonstrate hydro-mechanical material stability under representative load scenarios, a comprehensive laboratory testing programme is carried out. This comprises investigation of the sealing capacity of the combined seal system and impact of the so-called excavation-damaged zones (EDZ) as well as investigation of the hydro-chemical long-term stability of the seal in contact with different brines under diffusive and advective conditions. This paper presents experimental approaches and preliminary results from laboratory investigations on salt concrete and combined systems as obtained to date.

1 Introduction

The investigation programme of GRS (which is undertaken within the auspices of the LASA, LAVA and THM-Ton Projects) addresses sealing materials planned to be utilised in the shaft seals. The data acquired in the LASA, LAVA and THM-Ton projects will be used to assess the long-term performance of the seals with respect to the required hydraulic conductivity.

2 Results and discussion

This paper provides a short overview of the studies undertaken in DOPAS that are part of the LASA, LAVA and THM-Ton programmes. The results are taken from the respective final technical reports, published as Deliverables D3.29 (Jantschik et al., 2016), D3.31 (Czaikowski et al., 2016) and D3.32 (Zhang, 2016).

In Section 2.1, selected experimental investigations relevant for the hydro-mechanical long-term material behaviour according to the LASA programme are summarised. In Section 2.2, selected experimental investigations relevant for the hydro-chemical long-term material behaviour according to the LAVA programme are summarised. In Section 2.3, selected experimental investigations relevant for the hydro-mechanical long-term sealing behaviour according to the THM-Ton programme are summarised.

2.1 LASA programme

The LASA programme focuses on the hydro-mechanical properties of candidate seal materials in a salt rock such as MgO and cement-based salt concrete. The LASA programme (in conjunction with the LAVA programme, Section 2.2) aims to provide experimental data required for the theoretical analysis of the long-term behaviour of cement-based salt concrete and MgO concrete 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* construction in a former salt mine. The drift sealing element was constructed at the 945 m level of the mine in January 1992. The samples were taken from two different boreholes. The salt concrete is a mass concrete consisting of a cement matrix with crushed salt filler. At the time of sampling the seal had been subjected to convergence of the surrounding rock salt for approximately ten years.

2.1.1 Long-term deformation behaviour

The tests aim at determining the deformation of the samples in terms of strains and strain rates in order to describe the time-dependent uniaxial creep behaviour of salt concrete at different stress states. Uniaxial creep tests were performed in a rig in an air-controlled room at approximately 25°C. The results of the uniaxial creep test show that material behaviour is different at lower stress levels of 5 MPa and 10 MPa and at a stress level of 20 MPa. While strains are small at lower stresses, a distinct creep deformation occurs at a stress level of 20 MPa. The reason for the different deformation behaviour at various stress levels might be that the cement structure of the salt concrete bears at uniaxial stresses up to 10 MPa. Cement is expected to have an elastic material behaviour without viscoplastic deformations after the water curing process has finished. Therefore, no stable creep rates could be derived at lower stress. When the stress level was increased up to 20 MPa, the cement structure of the salt concrete was damaged. Consequently, the salt grit structure of the salt concrete was subjected to the load, and because of the viscoplastic material behaviour of salt grit, the specimens exhibited explicit creep behaviour.

2.1.2 Material stability

Triaxial compressions tests (TC-Tests) were performed in order to investigate the mechanical stability of salt concrete. Onset of dilatancy, start of gas flux and failure of the specimens were determined under different radial stresses. The objective of the TC-Tests was to develop a greater understanding of the deformation behaviour of salt concrete than developed through the uniaxial creep testing described previously. Damage tests were carried out on three salt concrete samples in a triaxial apparatus, and deformation and gas permeabilities were measured under various stress conditions. The results of the triaxial compression tests show that salt concrete exhibits reversible (elastic) and irreversible (plastic) material behaviour during the compaction phase. The compaction test phase was identical for all three specimens. During the deviatoric stress phase, the results of the tests are different due to different confining stresses. It is possible to identify the onset of dilatancy by the evolution of volumetric strains. In all three tests, the onset of gas flux is measured at higher deviatoric stress levels than the onset of dilatancy. The boundary for the failure of the specimen increases with higher confining stress, analogue to the onset of dilatancy. The onset of gas flux and the failure of the specimens occurred nearly at the same deviatoric stress level. Consequently, the test results show that the investigated salt concrete samples were gas-tight until the load limit was reached. Generally, no damage is expected in the salt concrete specimens below deviatoric stresses of 30 MPa.

2.2 LAVA programme

The LAVA programme focuses on the hydro-chemical properties of candidate seal materials in a salt rock. The chemical stability of cement-based sealing materials is of vital importance for the longevity of sealing elements. In scenarios where there is a permanent contact between an aqueous solution and the sealing element, dissolution and precipitation processes can occur which eventually might result in changes of porosity and subsequently mechanical stability. Two evolutions are conceivable: firstly, porosity and consequently permeability increase. This may lead to a loss of mechanical stability. Secondly, porosity could decrease due to a net increase of solid phase volume. This would result in a decrease of permeability (Meyer *et al.*, 2003).
The composition of the aqueous solution depends on the ambient host rock formation. For the present considerations, the most important mineral phases in salt rock are halite (NaCl), anhydrite ($CaSO_4$), gypsum ($CaSO_4$*$2H_2O$), sylvite (KCl), kieserite ($MgSO_4$*H_2O), polyhalite ($K_2Ca_2Mg[SO_4]_4$*$2H_2O$), carnallite ($KMgCl_3$*$6H_2O$) and kainite ($K_4Mg_4[Cl_4SO_4]_4$*$11H_2O$). Naturally occurring brines in equilibrium with rock salt are always saturated with respect to halite. Equilibration with other mineral phases leads to quinary (without Ca) or hexary solutions (with Ca), with the composition specific to the particular set of mineral phases with which the solutions have equilibrated. For example, equilibration with potash salts results in brines that are dominated by Mg^{2+} and Cl^- (Herbert, 2000).
The corrosion mechanism of sealing elements depends significantly on the construction material and the solution composition. NaCl-based salt concrete is stable against NaCl-saturated brine (hereafter referred to as “NaCl-solution”) but corrodes in the presence of high $MgCl_2$-concentrations. A specific $MgCl_2$-rich solution in equilibrium with halite, sylvite, carnallite, kainite, and polyhalite is of particular interest and hereafter is referred to as “Mg-rich-solution”. $MgCl_2$-based sorel cement shows an opposite behaviour to salt concrete: it is stable in Mg-rich-solution and corrodes in NaCl-solutions containing small amounts of $MgCl_2$ only (Krauke and Fliß, 2008).
The objective of laboratory tests executed by GRS was to investigate the reaction path and diffusive and advective transport mechanisms in salt and sorel concrete in contact with Mg-rich- and NaCl-solution. The experiments described below were performed in the GRS laboratory and are on-going.

2.2.1 Batch- and cascade experiments

The “Cascade experiments” are executed to investigate the reaction path between sealing material and solution. The cascade experiment is a sequence of batch experiments and has to be performed in air-tight vessels for the elimination of carbon dioxide. In any batch experiment, powdered concrete is exposed to solution in a defined solid-solution-ratio. Vessels are shaken in an over-head-shaker during the whole reaction time. If equilibrium is reached between concrete and solution, the solution is separated from solid and is exposed to new powdered concrete for the next cascade in the same solid-solution-ratio as before. This process is repeated until no free aqueous solution can be regained anymore after an equilibration step. Solution and solid phases are analyzed at the end of each cascade.
Before starting cascade experiments singular batch experiments were executed in each system (Sorel concrete / Mg-rich-solution, Sorel concrete / NaCl-solution, Salt concrete / Mg-rich-solution, Salt concrete / NaCl-solution). On basis of development of solution- and solid phase composition the reaction time between powdered concrete and solution until the equilibrium is reached was determined. Determined reaction times appoint the duration of each cascade in the following cascade experiments.

Sorel concrete A1 consists of characteristic Sorel phases (3-1-8-phases), anhydrite (CaSO) and some halite (NaCl). Batch experiments have showen that Sorel concrete typical 3-1-8-phases dissolve in contact with NaCl solution. After 11 days a further change in phase composition has not been observed. The analysis of the solution has revealed no significant change in its composition over total testing time. Consequently, each cascade in the cascade experiment in system Sorel concrete / NaCl-solution needs minimum 11 days. In batch-experiments with salt concrete and Mg-rich-solution the dissolution of typical CSH-phases (calcium-silicate-hydrate) could be observed by the increase of Ca-content in solution as result of Mg-attack. Equilibrium has been reached after circa 15 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.
The total chemical reaction path of a solution penetrating a geotechnical barrier can be reproduced by the cascade experiment until thermodynamic equilibrium between the original solution and the solid material is attained. In this way, chemical reactions which may occur by an intrusion of brine to a sealing element can be simulated in a short time (Niemeyer *et al*., 2014).

2.2.2 In-diffusion and through-diffusion experiments

In-diffusion and through-diffusion experiments have also been undertaken. For in-diffusion experiments, Sorel concrete samples, coated with Araldite on generate surface and one front side, were placed in tracer-spiked magnesium-rich NaCl-solutions. Literature research and calculations, which were undertaken to derive diffusions coefficients, had shown that the diffusion coefficient in concrete is small (1×10^{-13} to 1×10^{-15} m^2/s) (Mattigod *et al*., 2012). Hence, all samples are still being tested to gather more robust intrusion profiles.
Through-diffusion-experiments are executed in special diffusion cells. The concrete sample is installed in the diffusion cell and tracer-spiked brine is passed across the bottom of the sample. A second, non-spiked brine is passed across the top of the sample and is analysed with regard to its development of tracer concentration over time. Because of the concentration difference between brine 1 (spiked) and brine 2 (non-spiked), a diffusional transport of tracer molecules from the bottom to the top of the sample is expected. The diffusion coefficient can be calculated on the basis of these experimental data. The thickness of samples and the duration necessary for saturation prior to starting diffusion experiments is determined in preparatory experiments. Through-diffusion experiments aim furthermore at investigating the kinetics of chemical reactions by diffusive corrosion processes. In principle, two scenarios are conceivable: on one hand a parallel progression of diffusion and corrosion may occur, on the other hand diffusion may occur faster than the process of corrosion. This circumstance will be investigated by analyses of the solid sample using x-ray diffraction.

2.2.3 Advective corrosion experiments

Advective transport is another transport mechanism in porous media which may affect corrosion of sealing elements. Corrosion as a result of advective transport and its consequences for the long-term sealing capacity will be investigated in two types of advection experiments: advection experiments which aim at reaction kinetics similar to diffusion experiments and experiments for investigating the influence of corrosion on porosity and permeability of the sealing material. A concrete sample was loaded with fluid pressure (NaCl- / Mg-rich-solution) on one face in the first type of advection experiments. The effluent brine is collected on the other face. The sample surface is pressure-less cast in araldite in an advection cell. In regular intervals, permeability is measured and vessels for collecting brine are substituted. The individual brine samples will be analysed with regard to their composition. Additionally, the composition of each concrete sample will be investigated by decomposition and x-ray-diffraction. A conclusion and better understanding of corrosion mechanisms affected by advection processes in concrete is expected from these experiments.

The installation of the second advection experiment is very similar to the first experiment. The main difference is that the cylindrical concrete samples are surrounded by rock salt, thus exhibiting a circular contact zone. It is assumed that the contact zone is the primary pathway for brine and for the migration of nuclides. For these tests samples of the hollow rock salt cylinders with a salt concrete core described in Section 2.1.3 are used. The samples are exposed to a confining pressure until permeability is minimized. This process simulates salt creep onto an *in situ* sealing element. Afterwards, samples are placed in advections cells in the same manner as described before for concrete samples.

A further experiment on combined samples is in progress. The sample was tested with a NaCl-solution in the beginning of test. A radial pressure of 5 MPa in the beginning and 10 MPa in further process were brought to the sample. After the contact zone was closed up to a permeability of 10^{-18} m^2/s, radial pressure was reduced to 2 MPa for relaxing the sample. In the next step, NaCl-solution was changed to a Mg-rich-solution. Permeability increases in the beginning because of the high injection pressure and decreases after pressure was reduced. After two month of contact to Mg-rich-solution, permeability starts to increase again. This phenomenon results from chemical processes in the salt concrete as former investigations at GRS have shown: If the Mg-rich-solutions is brought in contact to 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 result of the pH decrease, Portlandite $(CaO)_2$ becomes unstable and decomposes into 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) (Niemeyer *et al*., 2014).

Hence, the dissolution of CSH-phases is also to observe in this experiment composition. But dissolution needs more time compared to the batch- and cascade-experiments with powdered concrete.

2.3 THM-Ton programme

Crushed claystone produced by excavation of repository openings is considered a favourable backfill and seal material for disposal of radioactive waste in clay formations, because of its many advantages such as chemical-mineralogical compatibility with the host rock, availability in sufficient amounts, low costs of material preparation and transport, and no or less occupancy of the ground surface for the excavated claystone. The crushed raw claystone shall be used for backfilling the repository openings and, mixed with bentonite, for sealing boreholes, drifts, and shafts. In the frame of THM-Ton Experimental Programme, GRS has characterised the excavated COX claystone and mixtures with bentonite with regard to the following important properties:

- Compressibility which controls the mechanical stability, interactions with the surrounding rock, and the hydraulic conductivity.
- Water adsorption capacity which determines the water saturation, retardation and the resulting swelling pressure.
- Swelling capacity which is required for sealing gaps between rock wall and seal, for supporting the surrounding EDZ against damage propagation and enhancing the sealing of the EDZ.

- Hydraulic conductivity which dominates water transport and radionuclide migration in the seal.
- Gas migration properties which control development of gas pressure in the repository to prevent the whole multi-barrier system from gas fracturing.

The geotechnical properties of the crushed claystone and mixtures with bentonite were determined also from the previous experiments, e.g., (Zhang, 2014). The most important results are reviewed briefly below.

Crushed claystone (COX) produced by excavation of the Andra's Bure URL drifts 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 for its suitability for use as a backfill material. In addition, fine-grained claystone powder with grain sizes of d <0.5 mm was mixed with the MX-80 bentonite of d <0.5 mm in different ratios. The claystone-bentonite mixture is considered to be used as seal material.

2.3.1 Compaction and permeability of crushed claystone backfill

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 respectively vary in a range of 1.45-1.82 g/cm^3. The samples were compacted in the GRS big triaxial apparatus with measurement of gas permeability.

The compressibility of the material is relatively high, i.e., its resistance against external load is relatively low. At stresses of 12–16 MPa, corresponding to the overburden pressures at depths of 500–600 m, the backfill can be compacted to a low porosity of 20% which is close to the rock porosities of 14–18%. The compaction leads to a decrease in permeability. The permeability of the coarse-grained backfill is higher than that of the fine-grained material at a given porosity. It is interesting that the permeability measured by flowing water through a sample (d <10 mm) is much lower than the permeability to gas. The low water permeability is attributed to the effects of water-induced swelling and slaking of the clay grains into the pores. The compacted samples exhibited very low water permeability of 10-19 m^2 at a porosity of 30%, while such low gas permeability was observed at lower porosities of 20–25%, depending on the grain size.

2.3.2 Sealing properties of compacted claystone-bentonite mixture

As seal material, crushed claystone shall be mixed with bentonite and compacted to certain densities to meet specific requirements for sealing boreholes, drifts, and shafts. Commonly, the seals must have a sufficient supporting capacity against damage propagation of the surrounding rock, a certain swelling capacity for sealing of gaps and interfaces between compacted blocks and the surrounding rock, and a low hydraulic conductivity against migration of radionuclides with fluids.

Fine-grained COX claystone powder (d <0.5 mm) and coarse-grained claystone (d <10 mm) were mixed with MX-80 bentonite (d <0.5 mm) in different ratios of COX/MX-80 = 100/0, 40/60, 50/50, 60/40, 80/20 and 0/100. The claystone-bentonite mixtures were compacted in Oedometer cell to a maximum load of 30 MPa. This leads to different dry densities of the mixtures from 1.56 kg/m^3 at the pure bentonite to 2 kg/m^3 at the pure claystone. The higher the fraction of the crushed claystone in the mixture, the higher density can be achieved by application of the same load.

The water content of each mixture increases with decreasing suction or increasing humidity. The moisture uptake at a given suction is proportional to the bentonite content of the mixture. In the wet environment at zero suction or 100% relative humidity, all the mixtures can take up large amounts of water up to 12% for the crushed claystone and 48% for the bentonite. The increase in water content is accompanied by volume expansion. At the high humidity of 96-100%, the compacted claystone can expand to a volume increase of 12%, while the other mixtures expand even more up to 20-40% due to more bentonite content.

The swelling capacity of the compacted mixtures was measured in semi-confined conditions. The annulus between sample and cell was filled with fine-grained quartz sand. The samples were pre-loaded to an axial load of 5 MPa and then fixed. Response of the axial stress was recorded to drying and wetting. The measurement shows that drying leads the axial stress dropping down to zero and wetting contrary causes a rapid increase in the stress to high levels: 3 MPa in the compacted pure claystone; 4.5–4.7 MPa in COX/MX-80 mixture in ratios of 60/40 and 40/60, and 7.6 MPa in the compacted pure bentonite. Flooding the compacted mixtures with synthetic pore water can increase the swelling pressure further to higher levels of 6–7 MPa. The observations suggest high swelling capacities of the compacted claystone-bentonite mixtures.

The water permeability of the compacted claystone-bentonite mixtures was determined by flowing synthetic clay water through the samples in Oedometer cells. It is obvious that all the compacted mixtures exhibited very low water permeabilities: $K_w = 2\times10^{-19}$ m^2 at 80COX+20MX-80, $K_w = 3\times10^{-20}$ m^2 at 60COX+40MX80, and $K_w = 2\times10^{-20}$ m^2 at 40COX+60MX-80. 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). Excavated raw claystone as backfill material and compacted claystone-bentonite mixtures as seal material have been comprehensively investigated. All the materials exhibit favourable geotechnical properties with respect to their barrier functions to prevent the release of radionuclides from a repository into the biosphere.

3 Acknowledgements

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Performance of Czech Bentonite Material in the Plug in Geological Disposal Demonstrations.

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The EPSP laboratory tests of bentonite B75_2013 got concentrated on determining a basic description of the material and the confirmation of its properties against the requirements that were set out in the beginning of the project. A set of experiments and expertises were performed in order to determine firstly basic chemical and geotechnical properties, being followed by test focused on manufacturing bentonite pellets for successful plug construction. Other test complemented the mentioned ones, starting with hydraulic conductivity and retention curves, being followed by construction of physical models. Those simulated partly the performance of the plug as the EPSP itself is not going to be dismantled during the course of DOPAS project. Firstly, the physical hydraulic model (PHM) got focused into bentonite saturation; on the other hand physical interaction model (PIM) aimed to observe into plug component material interactions. Those model were after defined time period dismantled and evaluated providing data for plug performance modelling.

1. Introduction

The Czech deep geological repository (DGR) concept assumes that waste packages containing spent nuclear fuel (SNF) assemblies will be enclosed in steel-based canisters placed in vertical or horizontal boreholes at a depth of ~ 500m below the surface. The void between the canisters and the host crystalline rock will be backfilled with compacted bentonite which will make up the final engineered barrier. It is presumed that the buffer material will originate from Czech Republic bentonite deposits. DGR safety will be enhanced by the efficient performance of the plugs and sealing systems which will make up an important part of the overall disposal system.
Several types of sealing plugs will be required, the function of which will be to provide for the sealing and closure of individual waste packages not only throughout the period of repository operation, but also following the permanent closure of the facility. Such plugs will have to provide a high level of resistance to the considerable pressure which will be exerted by hydrostatic forces and volumetric changes within the engineered barriers (Dvořáková et al., 2014).
The objective of the DOPAS international project is to design a sealing plug system for DGR use, provide detailed plans for the design of such plugs, test both the characteristics of the materials to be used and the construction technology and to install four experimental in-situ plugs. Four in-situ plugs have been constructed within this project. One of them is the plug within the frame of EPSP (Experimental Pressure and Sealing Plug) (Svoboda et al., 2016b), built at Underground Laboratory Josef, operated by Czech Technical University in Prague (CTU) - see Figure 1-1.

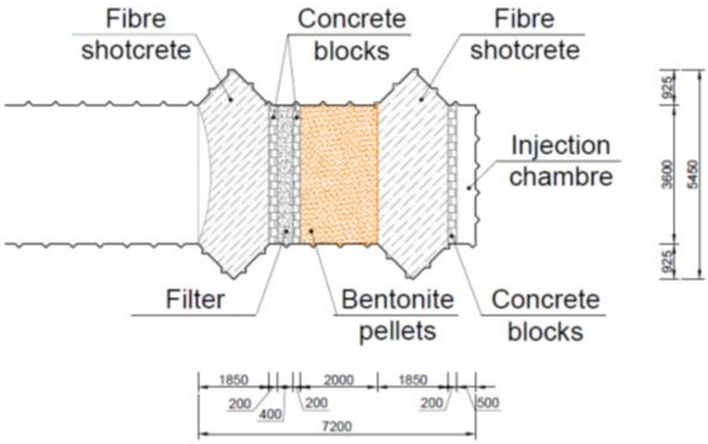

Figure 1-1- Scheme of the conceptual design of the EPSP. Dimensions in mm. (White, et al., 2013)

2. Scope and objectives

The main requirements toward using bentonite material for future Czech DGR repository plug were following:

- Local material (Czech origin)
- Non-activated bentonite
- Fulfilment of the various sealing requirements (see deliverable D2.1, White et al., 2013)
- Homogenous material
- Availability in sufficient quantity
- Availability in reasonable time

Commercially available "Bentonit 75" (B75) bentonite was found to be the only material readily available and able to fulfil all the above criteria. Non-activated Ca-Mg bentonite (Bentonit 75) is extracted from the Černý vrch deposit and is produced by Keramost, a. s. Therefore, the scope of activities presented was to assess properties and performance of bentonite and bentonite pellets, made from B75 toward DGR sealing plug safety performance. The B75 material for the EPSP construction was delivered in 2013, thus marked as B75_2013.

3. Laboratory tests

3.1 Bentonite and pellet characterisation

The initial EPSP laboratory tests got concentrated on determining a basic description of the material and the confirmation of its properties against the requirements set out in Deliverable D2.1 (White et. al., 2013).

3.1.1. Bentonite characterisation

The processing technology has been identified as the main factor affecting the properties of B75 produced in recent years. The resulting bentonite B75_2013 chemical composition is presented in Table 3-1. (Vašíček et al., 2016). Table 3-2 provides a summary of the basic geotechnical properties of B75_2013 (Vašíček et. al., 2016)

Table 3-1 Chemical analysis of bentonite B75

wt%	B75_2013		
SiO_2	49.83	**MgO**	2.88
Al_2O_3	15.35	**CaO**	2.01
TiO_2	2.82	**Na_2O**	0.67
Fe_2O_3	10.9	**K_2O**	1.05
FeO	3.74	**P_2O_5**	0.63
MnO	0.09	**CO_2**	3.66

Table 3-2 Basic geotechnical properties of B75_2013 bentonite material

Water content on liquid limit	171%
Specific density	2860kg/m^3
Hydraulic conductivity at dry density 1400kg/m^3	$4 \cdot 10^{-13}$ m/s
Swelling pressure at dry density 1400kg/m^3	2MPa
Thermal conductivity at 1400kg/m^3 and water content 6 and 20%	0.3 and 1W/mK

3.1.2. Pellet characterisation

A number of tests were conducted by CTU with respect to manufacturing the bentonite pellet. The main aim was to determine under which conditions the best bentonite compaction can be achieved resulting in the best possible dry density. Two most promising manufacturing technologies resulted into two types of "pellets" (B75PEL12 and B75_REC – see Figure 3-1 and 3-2). Influence of water content during pressing on final dry density of B75PEL12 is shown on Figure 3-3, comparison of final dry densities of both products is on Figure 3-4.
The B75PEL12 with a maximum dry density value of around 1800kg/m^3 was selected for further experimental purposes. The pellets have a diameter of 12mm, a length of up to 40mm.

Figure 3-1 B75 PEL12 material

Figure 3-2 B75 REC material

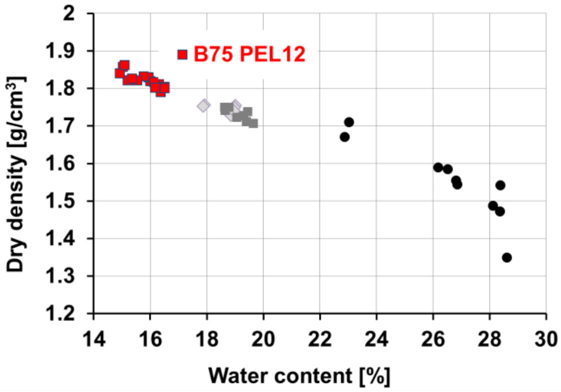

Figure 3-3 Influence of water content on B75PEL12 final dry density

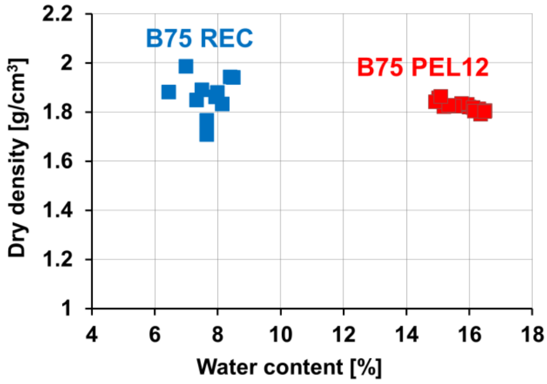

Figure 3-4 - Comparison of dry densities of both final products.

The CTU was also responsible for the construction of the bentonite seal of EPSP. Various emplacement tests were performed with the aim to achieve average dry density at least 1400kg/m^3 after installation. Tests included free fall pouring, pouring with vibration, using of dynamic compaction plates and spraying. As a result, the bentonite pellets (B75PEL12) were emplaced into the EPSP sealing section in horizontal layers with a maximum thickness of 3cm which were subsequently vibration compacted. Sprayed clay technology was used for the backfilling of the upper part of the drift. Approximately 5% (1.5m^3) was backfilled; with B75 REC (fraction 0.8-5). In-situ sampling during the construction phase confirmed achievement of the required dry density of the pellet layer (1400kg/m^3). More details are available in D3.20: EPSP plug test installation report (Svoboda et. al., 2016a) and in the contribution Svoboda et al. (2016b).

3.1.3. Bentonite pellet saturation and homogenisation

The homogenization of bentonite pellets was monitored during measurement of hydraulic conductivity. The Figure 3-5 shows the state before and after its saturation. Pellet homogenization is clearly visible.

Figure 3-5 State of bentonite pellets before (left) and after 3 days of its saturation (right). Picture in the middle shows the point of water entrance into the sample, the right one the material from the middle of the sample.

3.1.4 Bentonite and pellet hydraulic conductivity measurements

The values of the permeability/hydraulic conductivity of the bentonite materials will influence the nature and functionality of the EPSP experimental plug. Experiments were conducted on two types of experimental sample hereinafter referred to as "small cell/small samples" and "large cell/large samples" in the text. The interior dimensions of the experimental cells consisted of:

- small cell: diameter 30mm and length 15mm (permeability of compacted powdered bentonite B75)
- large cell: diameter 80mm and length 50mm (pellets compacted into the large cells; dry bulk density value of 1400kg/m^3)

The maximum pressure applied in the experiments was 2.0MPa (Vašíček et al., 2016).
Hydraulic conductivity varied for powdered B75 (dry bulk density 1400kg/m^3) varied between $4.78 \cdot 10^{-13}$ - $5.70 \cdot 10^{-13}$m/s (for input water pressure 1.6 - 2.0MPa) and for bentonite pellets $3.12 \cdot 10^{-13}$ - $3.23 \cdot 10^{-13}$m/s (for input water pressure 1.6 - 2.0MPa; Vašíček et al. 2016).

3.2 Retention curves (Block tests)

The moisture retention curve was determined using two methods. The first method was a block method (Villar, 2007), the second one was saturation measurement in the physical hydraulic model (PHM, see chapter 4). In the PHM the moisture retention curve was determined using the measured relative humidity values (after conversion to suction pressure) and the corresponding water content. The comparison of both methods is shown on Figure 3-6. The results indicate that, despite the difference in scale of the samples, they well compatible.

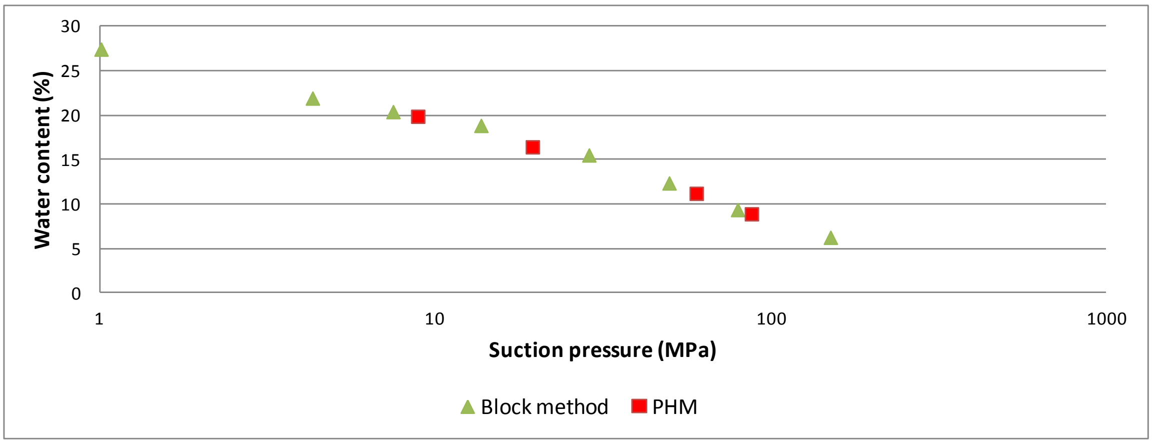

Figure 3-6 Comparison of the retention curves of bentonite B75 obtained by the block method and following the dismantling of the physical hydraulic model (PHM)

4. Physical models of plug performance

The EPSP experiment will not be dismantled during the course of the DOPAS project, therefore plug physical models at the laboratory scale were proposed. The aim of these experiments was to collect data for the subsequent calibration of numerical models of the bentonite material saturation.
Two types of physical model were constructed in the ÚJV's laboratories:

- **Physical hydraulic model - PHM**
- **Physical interaction model - PIM**

Detailed description is presented in Trpkošová et al. (2016) and Večerník et al. (2016).

4.1. Physical hydraulic model (PHM)

The aim of PHM was to describe the hydraulic and mechanical processes during saturation of bentonite. Two PHM tests were constructed, one with bentonite powder and the other with bentonite pellets. The both physical hydraulic models consist of nine stainless steel chambers of cylindrical shape with approximate dimensions 0.05m in length and 0.08m in diameter (total length of bentonite in PHM is 45 cm) and will be equipped with RH sensors to record the distribution of water content within the bentonite material.
The sample of compacted bentonite and pellets (the intentical materials as that used in EPSP) was fitted with measurement sensors and the sample was gradually saturated with water under pressure 2MPa. The results of the testing of the physical hydraulic models consisted of curves describing the development of:

- the volume of water which infiltrated into the sample
- the pressure under which the water infiltrated
- the development of RH at 9 observation points
- the development of swelling pressure at the end of the sample

The result examples for PHM with bentonite powder are shown on Figure 4-1 and Figure 4-2

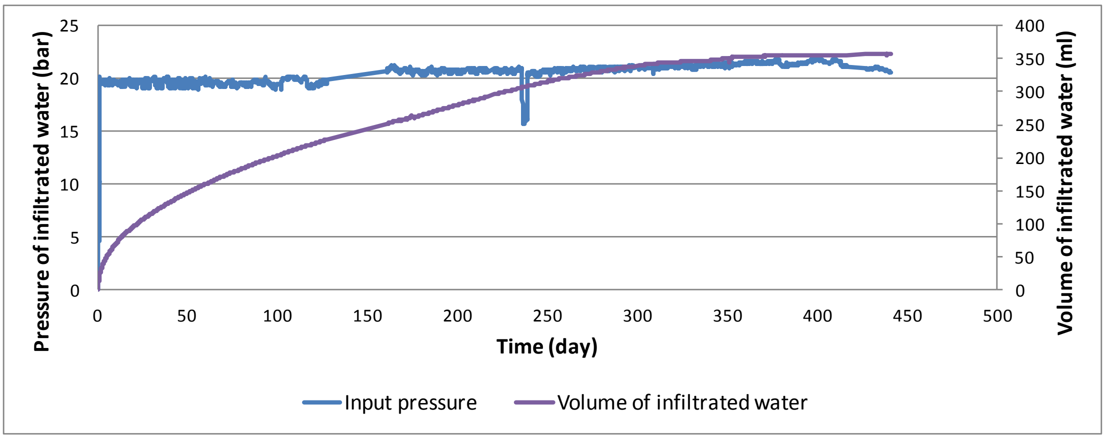

Figure 4-1 The pressure and water volume infiltrating the sample. Pressure drop around 230 days was caused by the failure of a pressure reducing valve (Trpkosova et al., 2016).

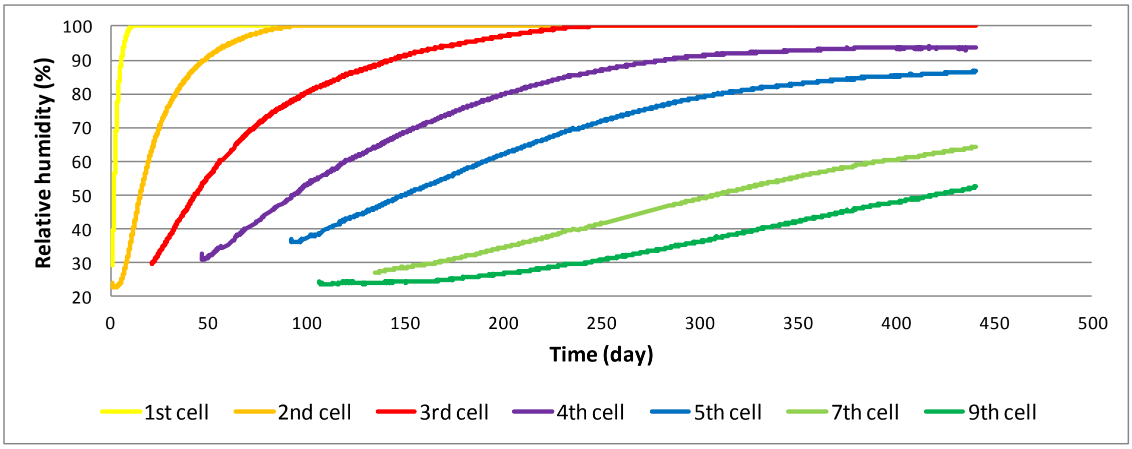

Figure 4-2 Development of the relative humidity in different observation points (Trpkosova et al., 2016).

4.2. Physical interaction model (PIM)

A physical interaction model (PIM) was dedicated to verification of anticipated interaction processes between the materials being used for the EPSP construction (e.g. changes in material properties, the formation of new phases, interaction of water with phases etc). The identical materials (concrete and bentonite) were used to those in the EPSP plug. Synthetic granitic water (SGW), under input 2 MPa pressure (as in Trpkosova et al., 2016), was used as the liquid phase.

The quantity of PIM water outflow was continuously monitored following the attainment of the steady state. The water was sampled for chemical analyses. The outflow exhibited significant enrichment in all major cations and anions in comparison to entrancing synthetic granitic water. A similar degree and enrichment content was observed in the output of the bentonite hydraulic permeability tests (PROP), see Figure 4-3. PIM dismantling focused on the determination of interaction products and so as to comparing the physical and chemical properties of the materials prior and after the experiment (i.e. mineralogy, porosity, CEC, pH of the leachate, chemical composition, etc.). The concrete part of the PIM acted as calcium source, exchanging for Na^+ and Mg^{2+} in bentonite (determined using cation exchange capacity, CEC). Bentonite material was also analyzed for the specific surface area (SSA) using EGME method (Carter et al., 1986). Although some minor difference in specific surface area along PIM bentonite samples were observed, generally the SSA values are close to the original bentonite B75_2013.
The results proved that some of the interaction processes occur. However, interaction experiment duration was not sufficient to observe or confirm expected changes (e.g. in mineralogy and physical properties etc.). All details of laboratory testing will be reported in final version of Deliverable D3.21 (Vašíček et al. 2016).

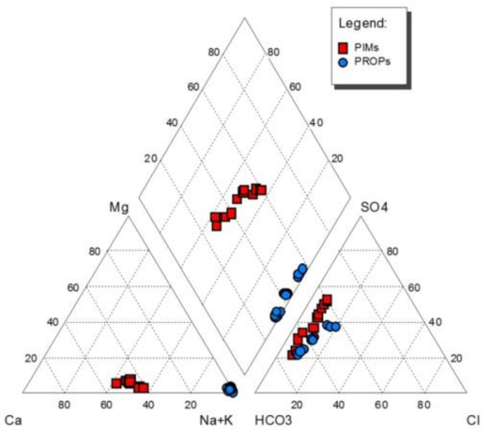

Figure 4-3 Piper diagram of PIM and PROP water samples (Vašíček et al., 2016).

5. Conclusions

The extensive laboratory research has supported bentonite material characterisation and property description in order to prove the ability for this material to be used for plug construction, even concerning pellet manufactured for this purpose. Eventhough the plug will not be dismantled during the course of DOPAS project, important data could be gained using laboratory models.

6. Acknowledgement

The research has been funded from the European Union European Atomic Energy Community (Euratom) Seventh Framework Programme FP7 (2007-2013) according to grant agreement no. 323273, the DOPAS project, and supported by SURAO. The project is further supported by the Czech Republic via funding provided by the Ministry of Education, Youth and Sports – institutional support grant no. 7G13002.

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9. DOPAS 2016 Seminar Session 5

Session 5 highlighted the role of plugs in safety and performance assessment even though the long term safety related issues were handled in almost all of the DOPAS 2016 presentations. Monitoring of plugs and seals and case studies related to the DOPAS were given in this session.

Chair: Dr. André Rübel works at Gesellschaft für Anlagen und Reaktorsicherheit (GRS), Germany. Dr. Rübel belongs to the Safety Analyses group of the Repository Safety Research division and is physicist with a PhD in Environmental Physics. He has 19 years of experinece in the field of nuclear waste disposal and 15 years at GRS. He is mainly working in the field of integrated safety assessment for national and international projects and is the Work Package Leader of WP5, Performance assessment of plugs and seals system.

Co-chair: Pär Grahm has a degree in Mechanical Engineering (B.Sc) 1993 and a degree in Energy Systems (B.Sc) 1997 from Mälardalen University, Sweden. He is head of the Repository Technology Unit at SKB, Swedish Nuclear Fuel and Waste Management Co, Sweden. He has 18 years of experience within the nuclear waste management area and is Experiment leader for the Dome Plug (DOMPLU) test in the DOPAS Project.

Session 5 Schedule and direct links to the DOPAS 2016 Session 5 presentations:

1300-1320	Instrumentation and monitoring systems for evaluation of plug responses in geological disposal demonstrations (DOPAS Project)	Erika Holt[1], Edgar Bohner[1], Torbjörn Sandén[2], Richard Malm[3], Jaroslav Pacovsky[4], Jiri Svoboda[4] and Matt White[5] [1]*VTT Technical Research Centre of Finland Oy, Finland* [2]*Clay Technology AB, Sweden* [3]*Sweco AB, Sweden* [4]*Czech Technical University, Czech Republic* [5]*Galson Sciences Limited, United Kingdom*
http://www.posiva.fi/files/4163/5.1_Bohner_DOPAS_Instrumentation_Holt-Bohner_et_al_20160526_final.pdf		
1320-1340	REM (Resaturation test at metric scale): Preliminary hydraulic simulation (DOPAS Project)	Antoine Pasteau[1], Jacques Wendling[1], Nathalie Conil[1] and Claude Gatabin[2] [1]*Andra DRD/EAP, France* [2]*CEA/LECBA, France*
http://www.posiva.fi/files/4164/5.2_Pasteau_REM_resaturation-assessment_Seminar-DOPAS-mai-2016_-_format_DOPAS.pdf		
1340-1400	Integration Of demonstrator activities in performance assessment: analysis of processes and indicators (DOPAS Project)	Jaap Hart, Ecaterina Rosca-Bocancea, Thomas Schröder and Jacques Grupa *Nuclear Research and Consultancy Group (NRG), The Netherlands*
http://www.posiva.fi/files/4166/5.3_Hart_NRG-DOPAS-v2.pdf		

1400-1420	Quantitative versus qualitative performance assessment of closure	Heini Reijonen[1], Pirjo Hellä[1], Nuria Marcos[1], Barbara Pastina[2] *[1]Saanio and Riekkola Oy, Finland* *[2]Posiva Oy, Finland*
http://www.posiva.fi/files/4168/5.4_DOPAS_reijonen_et_al_2016_final.pdf		
1420-1440	Towards robust models of well seals and plugs in CO_2 storage sites	Richard Metcalfe, James Wilson and Steven Benbow *Quintessa Limited, United Kingdom*
http://www.posiva.fi/files/4169/5.5_Metcalfe_etal_DOPAS_CO2_WellSeals(v1.0_230516a).pdf		

Instrumentation And Monitoring Systems For Evaluation Of Plug Responses In Geological Disposal Demonstrations

Erika Holt[1], Edgar Bohner[1], Torbjörn Sandén[2], Richard Malm[3], Jaroslav Pacovsky[4], Jiri Svoboda[4]

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[2]Clay Technology AB, Sweden
[3]Sweco AB, Sweden
[4]Czech Technical University, Czech Republic

Three of the five demonstration plugs within the DOPAS project had extensive monitoring systems installed to evaluate material and structural performance. The massive full-scale tunnel end plugs were placed in-situ and their performance was evaluated for both the early- and late-ages. The evaluated properties included aspects of concrete hydration, such as temperature rise, as well as any potential responses of the structure and materials to accelerated pressurization to simulate the design-life. Concrete structural monitoring includes properties such as strain and displacement, while the total and water pressure are evaluated behind and around the plug, and in some cases within a bentonite clay layer. The selection of monitoring systems, including both sensors and data collection, has provided insight which can be utilized in various other applications for material performance in challenging environments.

1 Background

Instrumentation and monitoring of performance of engineered barrier systems (EBS) are often an integral part of demonstration of safety of a repository. Monitoring of experiments, from lab-scale to full-scale in-situ demonstrations, help establish protocols for understanding material evolution and risks. The inputs from monitoring are used for conformance assessment compared to requires and provide feedback to the design basis. Information gained from monitoring of demonstrations such as DOPAS is also used to develop strategies for subsequent monitoring during the operational phase of a repository [Posiva 2009, Posiva 2012].

The plug monitoring and instrumentation plans developed within DOPAS have built upon the experiences gained in other recent demonstrations, such as Posiva's medium-scale buffer test [Hakola 2015], the Dome Plug test by SKB [Grahm et al. 2015] and Mock-Up-Josef by CZ [Šťástka 2011]. The design of monitoring systems for the DOPAS experiments required high durability to extreme underground environments. Many of the requirements of the monitoring systems can also be representative of future operational repository demands.

2 Scope and Objectives

2.1 Monitoring System Requirements

The relative humidity in the tunnels can be close to 100 % and the temperature is nearly constant at +10 to 12 °C. The maximum pH-value inside the concrete and back structure can be around 11 due to the use of low-pH cementitious materials. The material of sensors and cables should highly resist corrosion and therefore be made of stainless materials, e.g. copper, stainless steel or titanium.

The water pressure within the POPLU and DOMPLU demonstrations was defined to be up to 10 MPa. Since in the operational use of a deposition tunnel the maximum pressure will raise slowly, the pressure uptake in this demonstration experiment was accelerated by means of high pressure pumps. The sensors and cables needed to be covered by protection pipes where possible. The high pressure with a maximum of 10 MPa will be gradually decreased from the back to the front face of the plug and reaching 0 MPa at the front part of the plug. On the other hand, deficiencies in the sealing system and possible cracks in the rock mass and concrete can raise the water pressure almost to its maximum and therefore the cables of pressure sensors in the gap between the plug and rock have to be sheltered.

During the concrete casting phase, the sensors needed to be protected from concrete vibration work, by installing them as far as possible from vibration alleys and sheltering them with protection tubes. During the hardening and cement hydration process of the concrete, the temperature can raise up to 60 °C, which is usually not a limitation for normal types of sensors.

The high water pressure can damage the sensors, but it can also penetrate to the cables and connections. The cables are selected to resist high pressure, but also to pass through the lead through flanges to prevent any leakage through the wire or on the surface of the wire. Since the concrete shrinks after the casting phase, the wires are sealed against possible water leakage using different methods (e.g. small bentonite belts around cables, flanges, sealing of sheltering pipes).

The duration time of the DOPAS plug tests was assumed to be about 5 years and most of the sensors, cables and connections cannot be replaced or maintained during operation. Therefore they needed to be durable enough to be in constant function without service or maintenance for the entire operation time. Almost all sensors will be installed permanently inside the structure (inside the concrete plug, inside rock or inside bentonite clay) and therefore they needed to work reliably without any calibration during the entire test duration. A post calibration may be possible on a few sensors later on, during the decommissioning phase after the test has been stopped. Additionally, special concrete specimens with embedded sensors will be produced parallel to the casting of the plug and stored inside ONKALO to enable calibration of sensors after the test.

For the POPLU case, all materials used in the instrumentation and monitoring program needed to be pre-approved by Posiva regarding foreign materials used in ONKALO, so as to ensure the environmental safety of the site.

2.2 Monitoring System Components

The monitoring system for the plugs consisted of multiple components, which are each described here with their constraints. All components need to be calibrated prior to installation. They are typically assembled and subjected to a test run in laboratory conditions prior to on-site installation to the demonstration.

The plug sensors are selected to measure properties of the materials and structure during the concrete casting, the hydration process and finally the pressurizing phase. During and after the casting phase the pressure, humidity and temperature of the concrete are measured. In the pressurization phase, both the concrete condition and performance are measured by displacement sensors and strain gauges. Subsequently, the measurement results are compared to the structural behaviour of the plug and the surrounding rock mass. Sensor data provides feedback to design and modelling.

The sensor wires and sheltering are placed inside the concrete plug, in the gap between the rock and plug and in the different layers behind the plug. The sensor wires and their sheltering cables or tubes are selected to resist mechanical forces and high pressure. Water is not allowed to penetrate inside the cable, but should also not permeate using flow paths on the surface of the cables. The wires can pass through lead through flanges that prevent water leakage out of the structure. The wire and sheltering connects are critical for watertightness.

The data collection equipment, were designed based on sensor quantities and types. The measurement equipment should be suited for slow sample rate measurements over a long time period. Durability and redundancy aspects are also taken into consideration during the design of the system. Data collection is done from measurement computers, the main computer, IP cameras and the data loggers. Data can be downloaded on-site or can be connected to a local area network for transfer to a remote database.

The pressurization system used in some of the DOPAS experiments was to provide high water pressure simulating hydrostatic pressure and bentonite swelling. The pressurizing equipment should work reliably and keep the adjusted pressure behind the plug at various levels and rates. A pressurization system has main components such as two pressure piston pumps, two unloader valves, two electrical motors with gearing box, thyristors with automation and control units, electric centre, water tank, manifold connection pipes and main frame.

The near field monitoring of the plug includes assessment of leakage water volumes and chemical composition passing through the plug or rock fractures of the demonstration area. It can also include additional sensors placed in boreholes in the rock adjacent to the plug demonstration area. Such borehole monitoring can include water pressure, water leakage volume and chemical composition, temperature, strains and dislocations of the rock mass. The water used in pressurization can be marked with a tracer, such as sodium fluorescein, to evaluate the flow paths.

3 Methods

In all experiments, sensors were located in positions anticipated to have the greatest response. For instance, temperature sensors were placed at the centre point of the concrete that would have the greatest heat due to cement hydration during curing. Total pressure sensors were located along the plug circumference at the rock interface which could be subjected to leakage water. The sensor locations were planned in conjunction with the structural designers and modelling. Sensors were installed throughout the plugs' construction sequence. Sensors were attached to rock and reinforcement using tie wire and nails. Wiring and protective shielding were simultaneously connected and fed via lead-through pipes. Installation proved challenging and in some cases added complexity to the construction process, for instance by necessity to avoid creating of shadows due to obstacles created by monitoring equipment for the sprayed concrete in EPSP. The following sections give a short overview of the monitoring system locations, though more details can be found in project deliverables.

3.1 POPLU Experiment

The design of the monitoring system for POPLU is described in the Deliverable D3.25 [Hakola 2014]. POPLU's monitoring system had 141 sensors installed within the backwall, filter layer and plug section. The monitoring system of the tunnel backwall, filter and plug section one was routed 8 metres through the bedrock to the neighbouring tunnel (Demonstration Tunnel 3), while the monitoring system from the plug section two was fed via lead-throughs the front face of the plug in Demonstration Tunnel 4 (as seen in Figure 1).

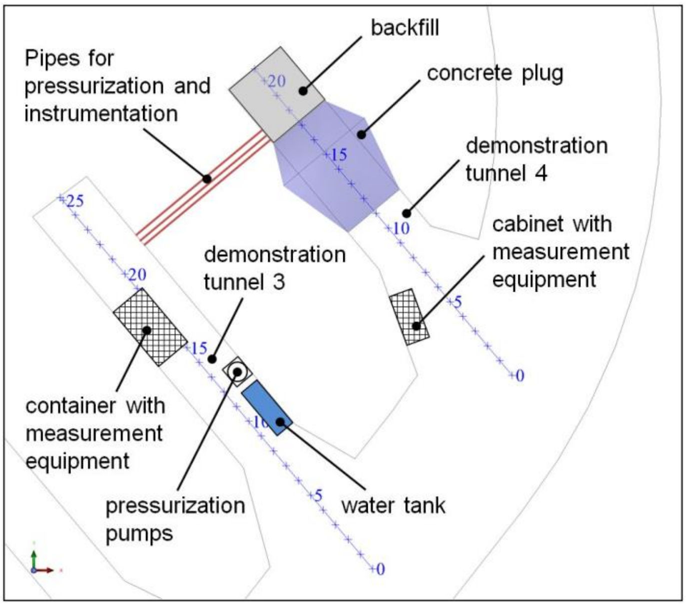

Figure 1. Top view of POPLU monitoring system arranged in demonstration tunnels 3 and 4, including pressurization system and data collection measuring equipment.

3.2 DOMPLU Monitoring

The design of the monitoring system for DOMPLU is described in the Deliverable D4.3 [Grahm 2015]. DOMPLU's monitoring system had 38 sensors installed in the concrete dome. In addition 45 sensors were installed within the backfill, the bentonite sealing and the filter layers. The monitoring system of the sensors positioned inside the bentonite sealing was routed 21 metres through the bedrock to a neighbouring tunnel niche, while the monitoring system from the sensors in the concrete dome was fed directly through the front face of the plug. The cables from a few sensors, positioned in the slot for the dome, were routed in a special lead-through in the front face of the plug. Figure 2 shows an overview of the experimental tunnel and the lead-throughs drilled to the neighbouring niche. The two uppermost lead-throughs were used for cables from sensors installed on the downstream side of the bentonite seal while the bottom lead-through was used for water pressurization pipes.

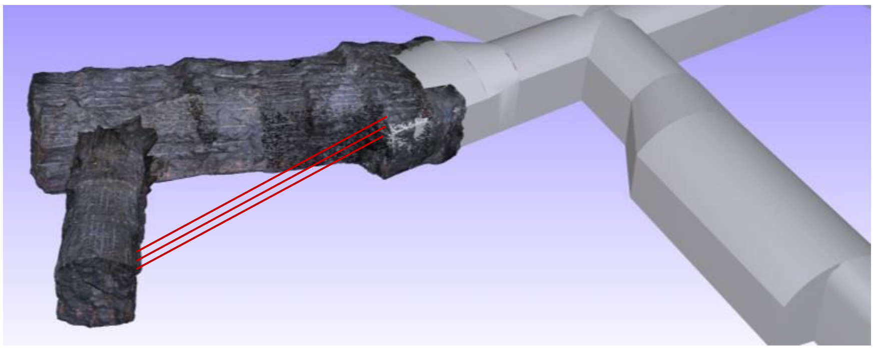


Figure 2. Left: Sketch of the three lead-through pipes going from the experimental tunnel,. b) photo of the lead-throughs inside the experiment tunnel.

3.3 EPSP Monitoring

The design of the monitoring system for EPSP is described in D4.7 [SÚRAO 2016]. EPSP's monitoring system had over 130 sensors installed within the backfill, filter layers, plug section and rock. To prevent possible longitudinal preferential path along the cable through the experiment, all sensors were connected via 23m long cased boreholes to the data loggers in the adjacent niche where all technology was installed. All the cabling was protect using stainless steel tubes inside the experiment. The set-up of the monitoring system in shown in Figure 3.

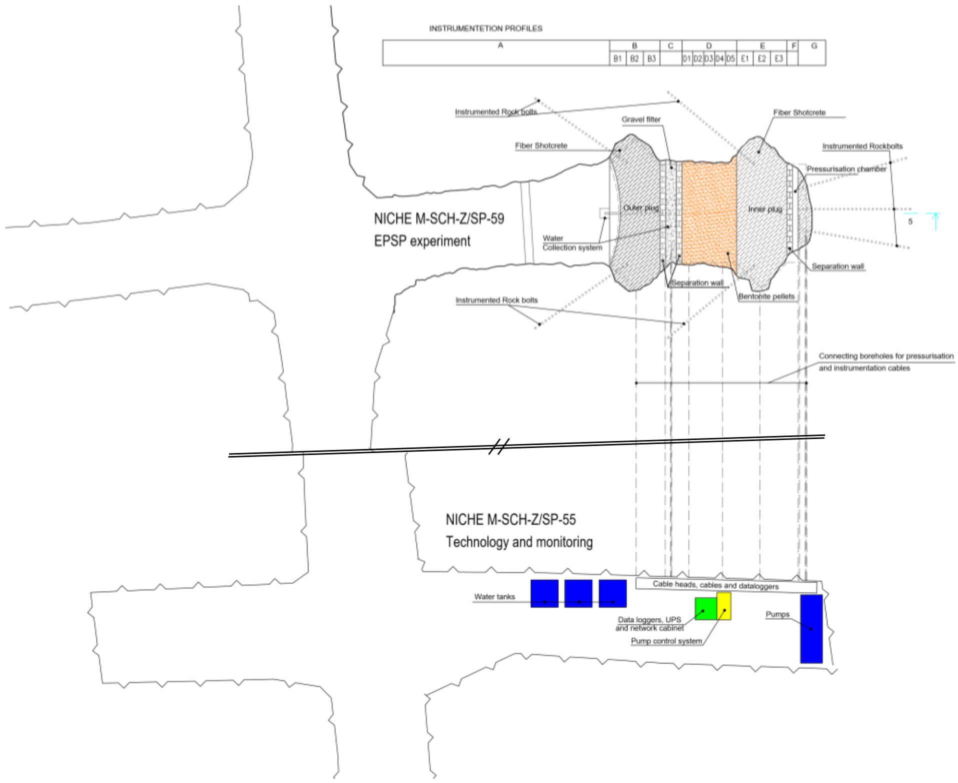

Figure 3. Top view of EPSP monitoring system arranged in SP59+SP55, including pressurization system and data collection measuring equipment.

4 Results and Discussions

Almost all of the installed sensors in the concrete plugs have worked successfully and captured the behaviour from before casting through pressurization. Monitoring of temperature, relative humidity, total pressure, pore pressure and displacement within the three experiments has demonstrated performance consistent with most of the design specifications. For example, the hydration temperatures during concrete casting have helped regulate the cooling system of DOMPLU and the formwork removal times in all experiments. Pressure sensors have shown the saturation level of bentonite clay within EPSP. Displacement sensors have shown the wedging effect of POPLU due to high pressurization. The work in the DOPAS 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.

There have been challenges with the monitoring system, which can be used as learned experiences for future EBS and repositories, and for other applications' complex monitoring scenarios. For instance, after grouting of the plug to rock interface, some sensors have failed as a result of the increasing water pressure. This was also as expected, since some of the concrete-related sensors were not designed to withstand the water pressure and contact with water was not always anticipated in some locations around the plug. During the build-up of pressure behind the plugs, all three experiments saw water-bearing fractures opened in the rock and leakage in the near field. Water pathways were also created in the concrete plugs themselves via some of the wiring cable bundles and thus leakage was measured independent of the plug watertightness. However, owing to the swelling of the bentonite seal layers and bentonite tapes, water leakages have decreased over time in all experiments.

The performance of all three plugs as detected from the monitoring systems has mostly been consistent with modelling predictions, providing confidence in the modelling and its application for detailed design of repository plugs. A parameter-by-parameter evaluation of the sensor components of the monitoring systems for each experiment is detailed in DOPAS Deliverable D4.4 [White 2016].

5 Conclusions

Monitoring systems were designed to assess plug performance based on properties of temperature, relative humidity, total pressure, pore pressure, strain and displacement of the concrete, clay and rock. The monitoring system was composed of sensors, wires and shielding, data collection systems, pressurization systems and near field monitoring including leakage assessment. In general, the monitoring systems of POPLU, DOMPLU and EPSP have performed well, and have been used to evaluate the performance of the experiment with respect to design specifications. The systems were designed and installed based on past experiences, including improvements to aspects especially related to watertightness for the extreme environment associated with pressurization. Monitoring results have fed back to the design basis and form an integral part of repository safety demonstration. The DOPAS monitoring system design and experience can also be utilized in various other applications when evaluating material performance in challenging environments.

6 Acknowledgements

We grateful acknowledge the many researchers, engineers and contractors who assisted in planning, calibrating, installing and interpreting results from the monitoring systems in the DOPAS experiments.

The research leading to these results has received funding from the European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013 under grant agreement no 323273, the DOPAS project. Complimentary funding provided by partner organization of Posiva, SKB, CTU and VTT which have contributed to the results in this paper are also acknowledged.

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REM (Resaturation test at metric scale) Preliminary hydraulic simulation

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Andra's experiment REM consists in the artificial resaturation of a mixture of pellets and powder of bentonite at a metric scale (Conil et al., 2016). It started around one year ago and evidenced the partial hydration of the lower part of the core. Blind simulations had predicted a full resaturation time of 30 to 60 years. No mechanical response (i. e. swelling pressure) has been measured so far. Hydraulic simulations have been conducted for a first comparison with measured relative humidity at some points. The computed hydration appeared to be consistent with reality at the macroscopic scale but local comparison proved to be difficult because of the still high heterogeneity of the partially hydrated bentonite at this early stage of resaturation. Longer measurements and further hydraulic and coupled hydro-mechanical modelling will be needed for deeper investigation.

1 Background

Andra's experimental participation to the DOPAS project is mainly twofold. The Full Scale Seal (FSS) demonstrator and a satellite experiment called REM. FSS is one of the various experiments implemented by Andra within the frame of the Cigeo Project (the French Deep Geological Repository) development, to demonstrate the technical construction feasibility and performance of the seals to be built in order to close the repository galleries and alveoli (shafts, access ramps, drifts, disposal vaults). The REM (Metric Scale Resaturation) experiment has been designed to study the water saturation of a bentonite mixture of 32 mm diameter pellets and crushed pellets used in FSS (Conil et al., 2015). The originality of this mock up is its scale. The cylindrical cell where the bentonite mixture is placed has a one meter height and one meter diameter. Water is injected at the bottom of the experiment at a very low controlled rate so as to simulate the natural resaturation flow from the clay host rock. REM contains several tens of gauges measuring pore pressure, total pressure, relative humidity and the swelling induced total strength on the experiment top cover. In-laboratory tests (at centimetric and decimetric scale) have been performed by the CEA/LECBA laboratory before the beginning of the REM experiment itself to get a better understanding of the bentonite behaviour under several conditions (water composition, dry density) and to characterize its hydro-mechanical properties. The REM results will be used to consolidate the representation of seals in the whole of CIGEO repository TH-Gas transient assessment and in safety analysis. To help this purpose, one mean is numerical simulations of the experiment.

2 Scope and objectives

REM metric-scale cell was installed and hydration started in September 2014. So far significant changes in relative humidity were measured at the bottom of the core whereas any significant changes in total pressure were measured. Uncoupled simulations (i. e. only hydraulic) have been done to assess water distribution within the core using a simple approach so as to quickly get a preliminary interpretation of its early resaturation. A coupled hydro-mechanical modelling will be conducted later on basis of in-laboratory tests results and REM future measurements in order to get a better understanding of its whole behaviour.

3 Modelling

The phenomenological model used for these hydraulic simulations was a generalized Darcy flow coupled with Van-Genuchten/Mualem empirical formulations to represent the non-saturated behaviour (i.e. retention and relative permeability curves). Due to resaturation the remaining porous air within the bentonite is driven out of the core and collected at the top of the cell where air flow is measured continuously. As a first approximation it was considered that air is perfectly mobile and thus any air pressure increase occurs within the core. Hence the Richards' theoretical approach was followed. No gravity was taken into account since capillary forces are much higher.

Despite its initial heterogeneity (pellets & powder) the bentonite core was modelled as a homogeneous material. Some of the physical and hydraulic data were taken from in-laboratory tests on samples conducted by CEA (porosity, initial saturation, intrinsic permeability). The parameters of retention curve were calibrated so as to fit the initial low relative humidity measured within the core (according to Kelvin's law) and to be consistent with data taken from previously laboratory tests conducted on similar bentonite mixtures (Gens et al, 2011). A classic law was chosen for relative permeability. All parameters are listed in Table 3-1.

Table 3-1. Hydraulic parameters

Constitutive law	Parameter	Value
	Porosity (-)	45 %
	Initial liquid saturation (-)	15 %
	Intrinsic permeability (m^2)	2.10^{-21}
Retention curve $S_e = \frac{S_l - S_{lr}}{S_{ls} - S_{lr}} = \left[1 + \left(\frac{s}{P_0}\right)^{1/(1-\lambda_0)}\right]^{-\lambda_0} \left(1 - \frac{s}{P_d}\right)^{\lambda_d}$	P_0 (MPa) λ_0 (-) P_d (MPa) λ_d (-) S_{ls} (-) S_{lr} (-)	50 0.43 800 4 1 0
Relative permeability $k_r = S_e^{\lambda}$	λ (-) S_{ls} (-) S_{lr} (-)	3 1 0

Water is injected at a constant rate of 50 mL per day through a porous disc below the core in order to make the inflow uniform. Hence a 2D-axissymetric model was chosen as a first geometrical modelling approach.

4 Results

Results in terms of relative humidity changes were compared during the early resaturation of the core (~ 300 days) at some points located in the lower part of the core – No significant change was measured at more than 15 cm from the lower boundary. The relative humidity was calculated from the computed liquid pressure according to Kelvin's law. The main results are depicted on Figure 4-1.

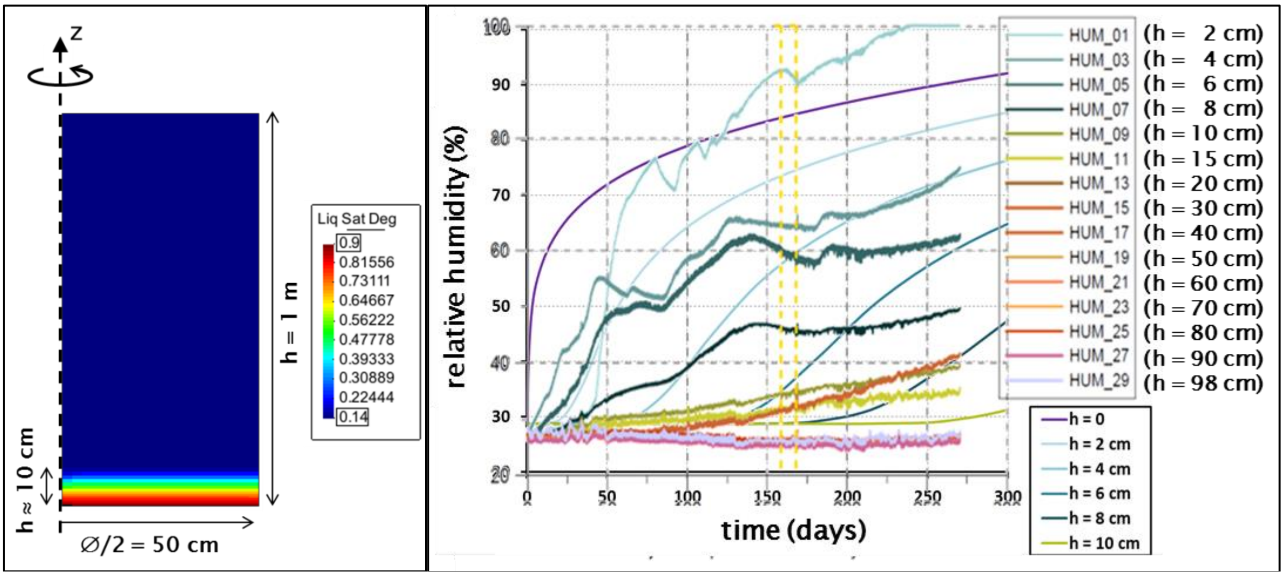

Figure 4-1. Liquid saturation field at time 265 days and relative humidity changes at different heights in the lower part of REM: Comparison between measurements and preliminary 2D-axissymetric simulations

The kinetic of computed relative humidity increase depends mainly on the distance to the bottom boundary of the core. The corresponding curves start to go up after a certain time (for instance 150 days at 8 cm height) thus showing a gradual progress of a saturation front. As the latter moves forward within the core the increase in relative humidity declines quite quickly because hydraulic diffusion increases with saturation. In particular the simulated relative humidity does not reach 100 % at the lower boundary. After 275 days of hydration it ranges from 30 % to 90 % within the ten first centimetres of the core.

The measures evidence a more complex evolution. Some of the sensors located in the first few centimetres show a very early increase of relative humidity whereas others show a later one. Thus no saturation front is evidenced. Afterwards relative humidity does not increase regularly within the ten first centimetres of the core. The sensor located at 2 cm height reached 100 % after 230 days of hydration, suggesting a full resaturation of the two first cm of the core already occurred. The other sensors show a relative humidity range between 35 % and 75 % after 275 days of hydration, which correspond to the order of magnitude of the results of simulations. However the local correspondence between measurement and simulation is very difficult.

5 Discussion

The results show the difficulty to compare computed and measured relative humidity so far with precision because of the important heterogeneity of the mixture at early resaturation (especially concerning retention properties). It seems that water flows locally quicker especially within bentonite powder where macro-voids are predominant. On the opposite bentonite pellets may be slower hydrated. Consequently a double porosity approach might bring deeper understanding in the hydration process. It has also to be noticed that longer measurement is needed to allow for a robust comparative analysis: According to blind hydraulic simulations the full resaturation time is estimated between 30 and 60 years (Robinet et al, 2014) whereas the REM hydration started only one year ago.

The absence of mechanical response so far may seem odd since the amount of water injected so far is not negligible compared to the initial available pore volume within the first 10 cm of the core (14 L vs ~30 L). Usually in most high scale experiments a partial resaturation of bentonite induces early and non-negligible increases in swelling pressure. To explain this apparent inconsistency it has been first assumed that a part of the injected water has been filling the porous disc (initially empty) since the beginning of the experiment. However this hypothesis has been rejected because the very high capillary forces in the bentonite coupled with a relatively low flow rate (2 mL per hour) enable bentonite to catch every water bubble as soon as it is injected in the porous disc, so it is unlikely that the latter has been accumulating significant amounts of liquid water. This conclusion was confirmed by 3D hydraulic simulations based on the same hypothesis as in 2D instead the modelling of the very permeable porous disc and local water injection through pipes (see Figure 5-1).

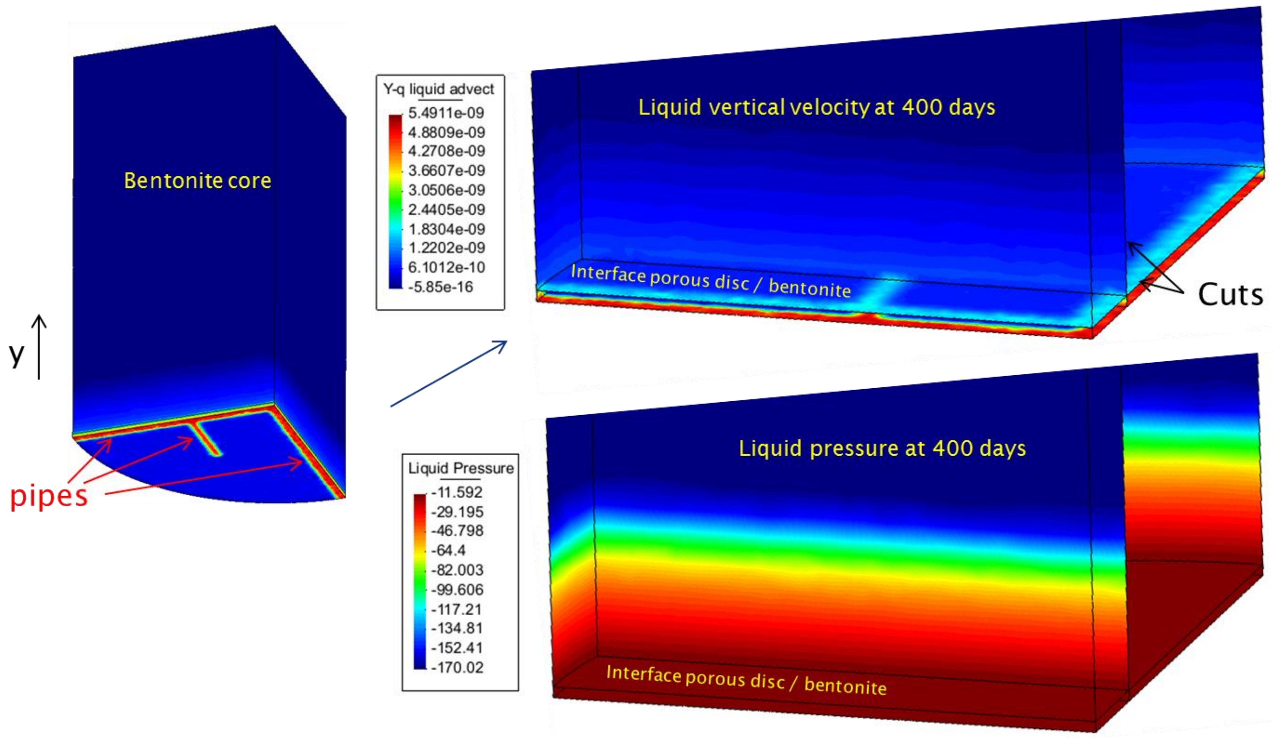

Figure 5-1. Computed liquid vertical velocity and liquid pressure field at time 400 days taking into account the porous disc through which water is injected

Another hypothesis to explain the absence of mechanical response is that the swelling potential may be weaker at this scale for (very) low degrees of saturation within the core. In-laboratory tests on samples seem to show that the early increase of swelling pressure is slower when scale is higher (Gatabin et al, 2015). Anyway and again it is difficult to conclude on this point at this stage regarding the very early state of the core hydration. Longer observations are needed for deeper investigation.

The constant imposed injection flow rate may become a problem when the bottom of the core is fully resaturated (filling of the porous disc instead of bentonite then risk of slight overpressures): bentonite may not be able to absorb it all as pores to be filled become more distant. According to predicting simulations fully resaturation of the bottom boundary of the core may occur between 500 and 700 days from the start of injection (depending on the considered value of intrinsic permeability

– 2.10^{-14} or 3.10^{-14} m/s). Thus later one may have to reconsider the experimental boundary condition (for instance change it into an imposed liquid pressure) to avoid problems in the injection circuit.

6 Conclusions

REM experiment started in September 2014 and is expected to last several decades for full resaturation of the instrumented metric scale bentonite core. Some relative humidity sensors evidenced a partly hydration of the lower part of the core and no mechanical response was detected so far. Preliminary 2D hydraulic simulations gave quite consistent results at the macroscopic scale but local comparison proved to be difficult probably because of the still strong heterogeneity of the mixture at this stage of very early resaturation. Longer measurements and further hydraulic and coupled hydro-mechanical modelling will be needed for deeper investigation.

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Integration Of Demonstrator Activities In Performance Assessment: Analysis Of Processes And Indicators

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As part of the European project DOPAS, NRG investigated how demonstrator monitoring activities can be coupled more closely to the performance assessment of a radioactive waste disposal, and developed and tested a methodology that allows the integration of demonstrator's results into the safety case. NRG aimed to develop a strategy for the integration of monitoring results by identifying indicators that are directly or indirectly measurable, and allow assessing the complete system behaviour.

SKB's concept of *safety function indicators* was a good starting point for identifying indicators, but in case related criteria are not met, these indicators provide insufficient information to substantiate the consequences for the long-term safety. A second principal limitation was the operation time: relevant processes, as resaturation of swelling clay, are rather slow and exceed the operational life time of the DOPAS demonstrators. This hampers the practical determination of parameters.

The tested *travel-time based indicator* was judged useful, allowing addressing processes upstream and downstream of the barrier independently. *Performance indicators related to safety functions* were found useful in quantifying the contribution of EBS-component to the long term safety. The principal parameter identified as relevant for plugs and seals is the *hydraulic conductivity* and is either related to clay swelling pressure and density, or to salt compaction and backfill pressure. Diffusion related processes are of less relevance because for most concepts and host rocks, diffusion cannot be avoided. Identification of monitorable parameters relevant for PA should therefore focus on hydraulic aspects, related to e.g. permeability, pressure, porosity, compaction, and convergence.

1 Introduction

Plugs and seals as part of the engineered barrier system (EBS) have essential roles in the design of radioactive waste disposal facilities, with the design basis and related criteria and requirements extensively reviewed in [DOPAS, 2014 & 2015]. Performance and safety assessments were identified as important step in the iterative process for developing the design basis [DOPAS, 2014]. NRG investigated how demonstrator monitoring activities can be coupled more closely to performance assessment (PA) calculations as part of the safety case, and developed, tested and discussed options to allow the integration of the results of technical demonstrators in a PA [DOPAS, 2016]. Presently the results of PA calculations are communicated in a safety case by so-called '*Safety and Performance Indicators'* [e.g. Becker *et al.*, 2009]. The definition of suitable indicators allows the analysis, understanding and communication of the outcomes of PA calculations. They can have a relevant role in supporting system understanding and providing evidence for safety, and thus are expected to contribute to the overall objective of confidence building. *Monitoring* of relevant processes *in-situ*, either in experimental or demonstrator systems, performed on real scale in URLs or in disposal facilities, can provide valuable evidence for safety.

2 Objectives

The objective of NRG's contribution to WP5 of the DOPAS project was to investigate how demonstrator monitoring activities can be coupled more closely to the outcomes of PA calculations, and develop and test approaches that allow the integration of technical demonstrator's results into a safety case. Presently the results of PA calculations are communicated in a safety case by s*afety* and *performance indicators*. NRG aimed to investigate a strategy for integration of monitoring results by identifying meaningful indicators that have two characteristics:

- the indicator is directly or indirectly measurable in demonstrators, and
- the indicator allows assessing the complete system behaviour.

3 Work procedures

For the preparation of the report, the five demonstrators that form the core of the DOPAS project where studied: *DOMPLU* (SKB), *ELSA* (GRS & DBE Technology), *FSS* (Andra), *EPSP* (SURAO), and *POPLU* (Posiva). The work was divided into five parts:

- Development and description of the overall methodology and extensions needed to include demonstrators in existing methodologies.
- Identification of (new) indicators.
- Qualification of the potential weight (or relevance) of the indicator on the (seal) performance status by discussing its potential impact on the overall safety.
- Establishment of a generic demonstrator case, and development and application of a suitable PA model representation to derive potential evolutions of the selected indicators in time.
- Analysis of the results of the actual demonstrator's projects performed in DOPAS.

The first parts of the work were performed on a generic level, observing that SKB's concept of safety function indicators and criteria [SKB, 2006] provides a good starting point. The generic demonstrator case study was based on the *ELSA* shaft sealing concept for a disposal in rock salt.

4 Results

Based on the lessons learned, a stepwise approach was proposed to identify suitable indicators and evaluate their monitorability:

1) Analyse the general properties of the disposal concept, related safety functions, FEPs, and scenarios, and - if available - existing indicators and criteria related to the barrier.
2) Establish key features and processes, and the system-specific underlying processes and parameters.
3) Evaluate potential indicators and the related parameters.
4) Estimate the relative contributions of diffusive and advective processes to the overall mass transport of radionuclides and deduce the relevance of the barrier of interest for the overall safety by relevance based indicators.
5) Investigate the technical feasibility to monitor the parameters of interest.

Based on this stepwise approach, a PA representation of a demonstrator test case was developed, based on the *ELSA* shaft seal concept for a disposal concept in rock salt [Rübel *et al*., 2016], and several indicators were evaluated. The PA model developed by GRS as part of the DOPAS project assesses the performance of the *ELSA* shaft sealing by calculating the amount of brine inflow, through the different shaft layers into the model repository. In the GRS simulation, properties of the shaft and repository (e.g. porosity, permeability) were assumed constant. NRG adopted the following assumptions for the demonstrator case:

- The shaft was modelled as a single porous medium with averaged properties.
- A layer of brine with constant properties on top of the shaft models the flooding scenario; as a result brine percolates through the shaft into the repository (1).
- The infrastructure area of the repository is modelled as a single segment containing salt grit backfill and converges as result of the overburden's pressure (2). The convergence rate in dry (initially) and wet (after start of the brine inflow) conditions is simulated by process models describing the compaction behaviour of salt grit [Schröder *et al*., 2009b].
- As soon as the volume of the brine inside the infrastructure area of the repository equals the pore volume of the compacting repository, the inflow of brine stops and is subsequently reversed (3) due to the ongoing compaction of the repository volume. This effect was not taken into account in the GRS simulations.

Figure 4-1 depicts the segment model structure for the ELSA shaft sealing concept (GRS, left) and the generic demonstrator case (NRG, right). The main difference between GRS's model and NRG's demonstrator case relates to the assumptions made for the backfill of the infrastructure area of the repository: in the GRS model the infrastructure volume is backfilled with non-compacting gravel, whereas in NRG's demonstrator case compacting salt grit is assumed as backfill. Assuming a compactible salt grit backfill enables the repository volume to converge and squeezing out of trapped brine and, if present, any dissolved radionuclides.

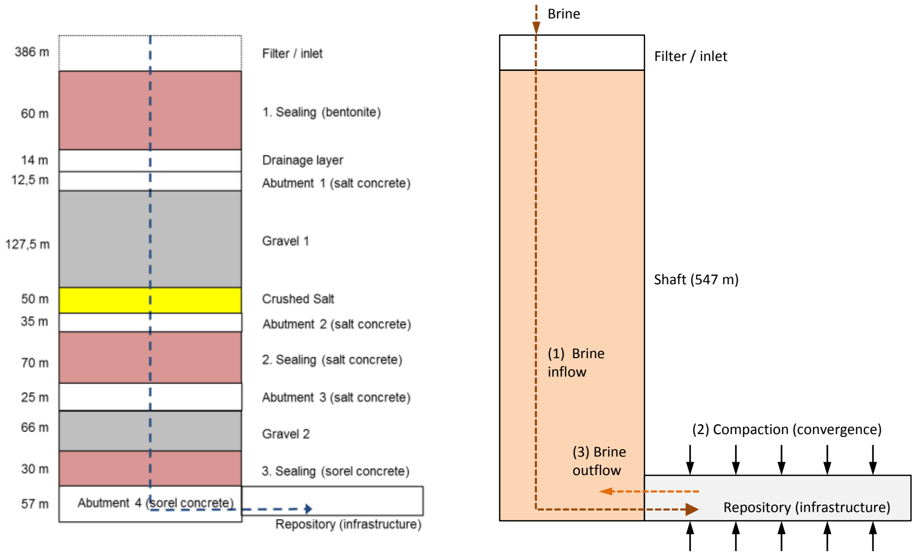

Figure 4-1: Set-up of NRG's generic demonstrator case (right) based on GRS's PA model (left)

The overall system behaviour of the modelled repository is shown in Figure 4-2. By imposing a constant initial convergence rate ($1 \cdot 10^{-4}$/a), the repository pore volume decreases in time. Starting from 700 years, brine percolates slowly into the repository, until full saturation is reached at approximately 41'000 years. From that time on, brine present inside the repository is squeezed out due to the ongoing convergence of the repository. The outflow of brine is restricted in the time interval to 58'000 years due to the hydraulic resistance of the vertical shaft. As a result of the ongoing convergence of the repository, the salt grit backfill will be compacted as time progresses. Consequently the porosity and the permeability of the backfill decrease. At a certain point in time (here: about 80'000 a) the repository' effective pressure equals the backfill stress, and the ongoing convergence rate is slowed down significantly, as is the outflow of brine.

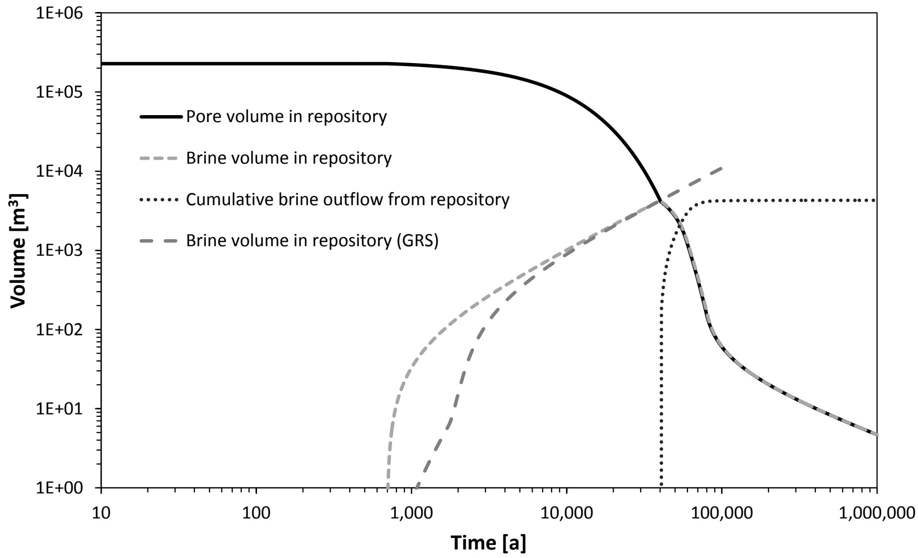

Figure 4-2: Evolution of repository and brine volumes

Combining the system behaviour described above with a travel-time based indicator [Schröder *et al.*, 2009a] provides insight about the breakthrough of radionuclides into the repository. In the present generic demonstrator case the following assumptions were applied:

- Three different initial convergence rates for the repository pore were considered.
- For the safety indicator *radiotoxicity flux to the geosphere*, a reference value of 0.1 Sv/a at the exit of the repository was assumed [Becker *et al.*, 2009].
- Given the long time period until the outflow of brine starts (several ten thousands of years), it was conservatively assumed that all brine from the disposal is directly entering the geosphere.
- Conservatively, a perfect mixing of the brine in the infrastructure area was assumed.

The travel time indicator can be calculated by dividing the reference value by the outflow of brine from the repository, and is depicted in Figure 4-3 for three different initial convergence rates.

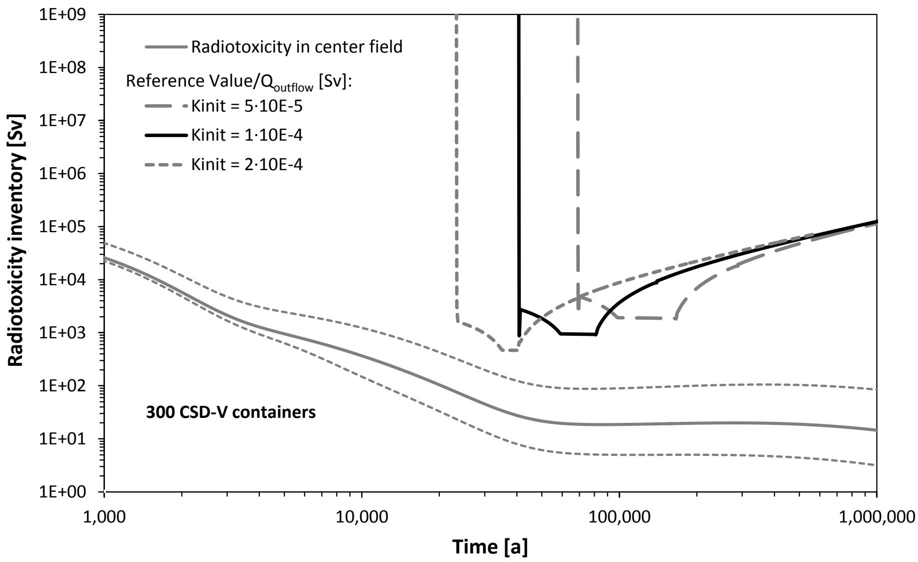

Figure 4-3: Evolution of indicator and radiotoxicity in repository for three initial convergence rates k and an inventory of 300 CSD-V containers

These curves in Figure 4-3 represent the maximum concentration of radiotoxicity that can be present in the repository without exceeding the given reference value, and can be compared with the evolution of the total radiotoxicity in that compartment (best fit: grey solid curve; uncertainty range: dotted curves). These curves are based on an assessment of a borehole from the generic Dutch disposal concept in rock salt [Schröder *et al.*, 2009b], with a salt grit sealing plug compacting as result of convergence. The inventory consists of 300 containers with high-level waste (HLW). A flooding scenario of the borehole combined with an immediate failure of all canisters was assumed. The figure shows that even for the very conservative and unlikely scenario assumptions and for all assumed repository convergence rates the radiotoxicity in the repository remains below the indicator value at all times, i.e. the plug performs sufficiently well.

5 Discussions

The following observations apply to the results of the generic demonstrator case study:

- The presence of brine is crucial in relation to the long-term safety of the repository and can be easily measured, e.g. by electrical conductivity. However, currently no mature technology is available to monitor over such long timescales.
- The presence of brine at various locations inside the shaft can in principle be detected in time frames shorter than several hundred years. If brine would be detected inside the shaft this information may help to analyse in detail the consequences of repository flooding.
- A parameter that is relatively straightforward to measure and that provides relevant information about the development of the repository system, including the shaft, is the pressure: the pressure inside the shaft can provide information about the convergence of (parts of) the shaft, and therefore the further reduction of the permeability and resistance to brine intrusion.

In general shows the *ELSA* shaft sealing case study that the applied travel-time based indicator is a useful tool, because it allows addressing processes upstream and downstream of the barrier independently. The indicator provides system understanding that can be used to identify measurable parameters which can be linked to long term safety indicators. However, it also shows that it needs (apart from understanding of the initial condition during operation) a detailed system understanding in order to extrapolate the operational conditions over long time frames. The approach illustrated for the barrier systems in rock salt is expected to be applicable in other (non-salt) systems as well.

6 Conclusions

SKB's concept of *safety function indicators* [SKB, 2006], including quantitative *criteria*, provides a good starting point for identifying indicators, but these indicators do not provide information on the safety in case criteria are not met. This makes it difficult to substantiate the consequences for the long-term safety. Nevertheless, the identification of safety functions for repository components is of vital importance for the development of a monitoring programme. Another limitation noted for the DOPAS demonstrators was their relatively short *operation time*: relevant processes, e.g. the resaturation of swelling clay, are rather slow and full resaturation of the barrier often exceeds the operational life time of the demonstrator. The slow evolution of the identified processes may hamper the practical determination of parameters regarded relevant for these processes: monitoring of processes may provide significant evidence for a safe evolution only over time intervals that cannot be realized due to technical limitations.

The tested *travel-time based indicator* was judged useful, because it allows addressing processes upstream and downstream of the barrier independently. Different assumptions and scenarios can be coupled, and can directly be related to relevant parameters. The *safety function indicators* and *performance indicators related to safety functions* are useful in identifying monitorable indicators, either because they may underpin statements on safety, or allow quantifying the contribution of each safety function or EBS-(sub)component to the long-term safety.

The principal parameter identified as relevant for the long-term safety is the *hydraulic conductivity*. The hydraulic conductivity can be related to the plug's sealing element or the buffer and backfill in the disposal cell. In case of swelling clay material, the related processes are the swelling pressure and density of the clay, and in case of salt grit the related processes are the salt compaction and backfill pressure. Other relevant key processes are the pressure gradient over the barrier, sorption, and solubility of radionuclides, with the latter two usually determined in independent batch experiments. Diffusion related processes are of less relevance, because for most concepts and host rocks, diffusion cannot be avoided. Identification of monitorable parameters relevant for PA should therefore focus on hydraulic aspects, related to e.g. permeability, pressure, porosity, compaction, and convergence. For disposal systems in rock salt, the presence of brine is an important monitorable parameter. Because most of the related parameters cannot be monitored either in demonstrators nor *in-situ*, they must be determined through indirect measurements or laboratory experiments. The derivation of these parameters involves process assumptions as a rule.

7 Acknowledgements

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Quantitative vs. Qualitative Performance Assessment of Closure

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Safety functions set for the closure system of the KBS-3 repository help to define the more detailed requirements set for the design and its overall performance. The maturity of these safety requirements and design define how different closure components and their performance are handled in the safety case. In Posiva's case, the safety case for OLA (operational license application) is being prepared before the final design of closure for the licensing documentation. For the licensing, there is a need to assess the long-term safety of the closure based on a well-defined design. However, in the case of closure, requirements and design development are greatly affected by the fact that the implementation of closure will happen decades after the licensing process, leading to a need to maintain flexibility in the design, so that it can be further developed during upcoming years. There are two ways of assessing performance (deterministic approach) of a given system, qualitatively and quantitatively. Qualitative understanding is needed to build conceptual models. This is essential in order to develop credible numerical models and thus have meaningful results from the modelling efforts. A qualitative assessment is also needed when there is no quantitative information or a model available or when requirements are such that detailed numerical modelling work cannot be called for (e.g. very long-term performance or qualitative requirements). In the safety case, the performance of the closure is discussed mainly in two reports, performance assessment and complementary considerations.

1 Introduction

Posiva is developing a new safety case for the KBS-3 repository at Olkiluoto, Finland, (Figure 1) to support the operation license application (OLA). At this stage, operational aspects are of growing importance in order to show practical feasibility of the repository construction and performance. Regarding closure, objectives of the safety case in this respect need to be set to reflect the fact that the actual implementation of the closure is decades away from the start of the operation. Nevertheless, at the time of granting operation license, the design and function of the closure needs to be assessed in detailed enough level, in order to:

- Present a reference solution that can be shown to be feasible to build,
- Have confidence on the performance of the closure design presented, so that its implications for overall long-term safety are understood and,
- Allow guidelines to further design development and optimisation of closure during the coming years.

1.1 Closure of a KBS-3 repository

The closure of the KBS-3 repository consists of the backfill and plugs in the underground openings that are located outside deposition tunnels (see Figure 1). Closure design in the previous safety case was generic and safety case was based on a reference solution (Figure 2), where backfilling material types and potential concrete based plugging was presented without providing details on composition and dimensions. The closure is part of the Engineered Barrier System, and thus has safety functions assigned to it.

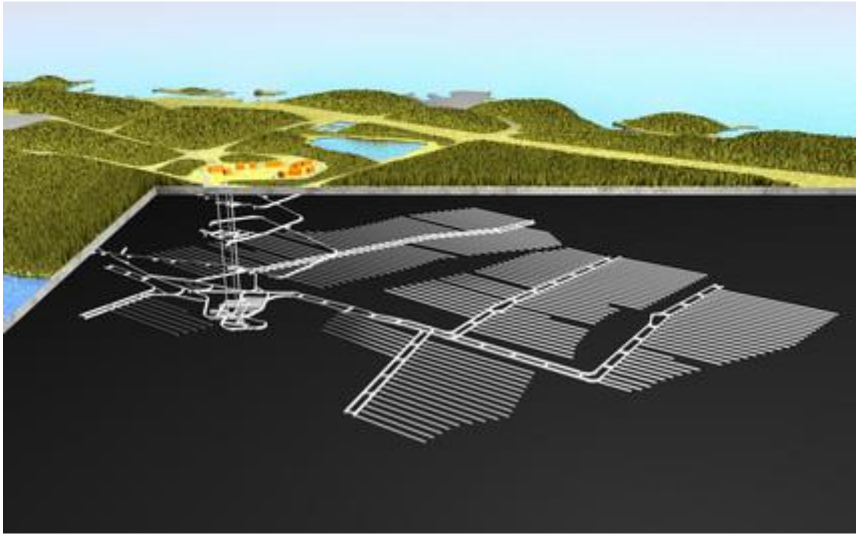

Figure 1. Schematic presentation showing the repository and its access routes (Posiva). Deposition tunnels are shown as parallel tunnels; all other tunnel volumes are part of the closure.

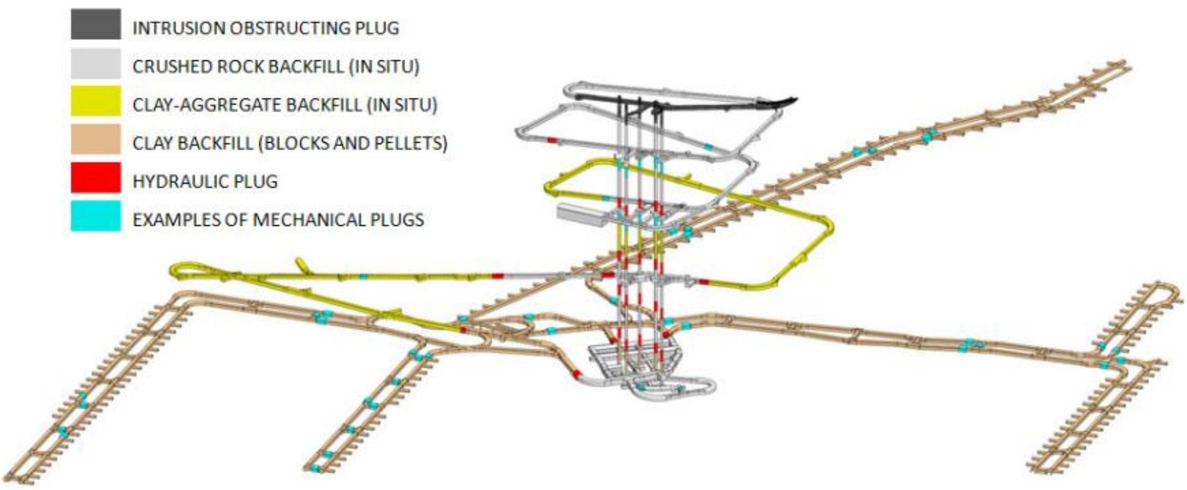

Figure 2. Materials in the reference design for the closure in the construction license application (Sievänen et al. 2012). The type and location of plugs at different depths is just illustrative.

1.2 Safety functions and performance

In case of closure, most of the safety functions aim at protecting the repository itself. Safety functions of the closure in Posiva's previous safety case (Posiva 2012) were defined as follows:

- Prevent the underground openings from compromising the long-term isolation of the repository from the surface environment and normal habitats for humans, plants and animals.
- Contribute to favourable and predictable geochemical and hydrogeological conditions for the other engineered barriers by preventing the formation of significant water conductive flow paths through the openings.
- Limit and retard inflow to and release of harmful substances from the repository.

Assessing performance of the repository system is guided by the requirements set for each engineered barrier component within the repository system. These long-term safety requirements, i.e. design basis (see Posiva 2012a), are based on the regulatory guidelines and a series of the iterations between long-term safety assessment and design work. Performance of a given component in the repository system is assessed with respect to the different performance requirements (performance targets).

While requirements for an individual closure component may be less stringent than those for near-field components, its functionality is assessed mainly as how closure supports the overall performance of the repository and how closure structures interact with other system components during the long-term evolution of the repository

2 Assessment of closure performance in Posiva's safety case

Posiva's safety case methodology consists of describing the design basis, the main features, events and processes affecting (or potentially affecting) the barrier system, describing the initial state and the main lines of evolution (referred to as "performance assessment") and assessing the consequence of uncertainties through scenarios to be analysed for their radiological consequences. In addition to quantitative performance assessment, qualitative complementary considerations about the evolution and performance of the barriers will be presented as well. The safety case will be presented in the form of a report portfolio reflecting the methodology above. The Design Basis report describes the chain of requirements:

Safety functions → performance targets → design requirements

Safety functions describe the roles of the barriers at high level. Performance targets refer to the performance of the barriers during the long-term evolution and design requirements describe the design features that should be fulfilled at the initial state (See Table 1 for closure).

Table 1. Performance targets and design requirements defined for closure in TURVA-2012 safety case (Posiva 2012a).

Performance targets for closure (Posiva 2012a):
Closure of the disposal facility includes backfill and plugs in access and central tunnels, shafts, miscellaneous excavations, and investigation holes. Different types of closure components may be used in different parts of the repository volumes. Closure shall complete the isolation of the spent fuel and support the safety function of the other barriers.
Unless otherwise stated, the closure materials and structures shall fulfill the performance targets listed below over hundreds of thousands of years in the expected repository conditions except for incidental deviations.

Closure shall complete the isolation of the spent nuclear fuel by reducing the likelihood of unintentional human intrusion through the closed volumes.
Closure shall restore the favourable, natural conditions of the bedrock as well as possible.
Closure shall prevent the formation of preferential flow paths and transport routes between the ground surface and deposition tunnels/deposition holes.
Closure shall not endanger the favourable conditions for the other parts of the EBS and the host rock.
Design requirements (Posiva 2012a):
The ground surface of the disposal area shall be landscaped to resemble its natural surroundings.
Structures and materials that considerably obstruct unintentional intrusion shall be utilized in the closure of the uppermost parts of the facility and investigation holes extending to the ground surface.
Structures and materials of the closure components shall be selected in such a way that the isolation functions of closure can be provided despite possible loadings related to glacial cycles, such as permafrost or changing groundwater chemical conditions.
Rock materials shall be used increasingly as backfill when moving from the disposal depth up to the ground surface due to the increasing risk of clay erosion.
Closure as a whole shall be so designed that the hydraulic connections from the disposal depth to the surface environment through the closed tunnels, shafts, and investigation holes are not better than through existing natural fractures and fracture zones.
Sections in the underground openings intersected by highly transmissive zones such as the HZ20 structure shall be hydraulically isolated from other facility sections.
The closure as a whole shall be so designed that short-cuts from the deposition tunnels/deposition holes to existing significant groundwater flowpaths are prevented.
The closure components shall keep the backfill and plugs of the deposition tunnels in place.
The amount of chemical species harmful for canister/buffer/deposition tunnel backfill/host rock in closure components shall be limited.

2.1 Description of the Initial State

The 'Initial state report' will describe the features of the closure design that are essential for the safety case. Initial state of the closure is the state after emplacement when direct control over a specific part of it ceases and only limited information can be made available on the subsequent development of conditions in that part of the system.

Operational aspects are seen as of growing importance and are taken into account in a more systematic way in the next safety case through failure mode and effect analysis (FMEA) (see e.g. Stamatis 2003 for a general description). The potential deviations caused during operation should be identified and assessed for their implication on long-term safety. FMEA process analyses the implementation process of the repository project and focuses on such events during the production process that could be left unnoticed and thus lead to deviations at initial state. These deviations essentially describe the situations where the as-built state of the repository goes beyond the design and its tolerances. FMEA is applied to all the components of the repository system, in order to map potential operational failure modes that could lead to deviations from the planned initial state.

FMEA is carried out for closure at level of detail consistent with the development of the design. In this work, knowledge based on the deposition tunnel backfill and deposition tunnel plug can be greatly utilised. The FMEA process will identify a set of potential deviations that will be used as source of information when formulating the scenarios for the repository system evolution. The deviation analysis is a qualitative analysis, for which, in some cases, quantitative information can also be provided in the form of probabilities.

2.2 Conceptual understanding and geological time scales

Qualitative analysis and understanding of the processes that potentially affect the repository system is of essence in building conceptual models. This is also the case with respect to closure. Features, Events and Processes (FEPs) screened for a site-specific safety case need to be elaborated during the assessment work (see e.g. Posiva 2014). In case of closure, in this regard, the most important issues are related to degradation of the materials and structures used in closure. How do different materials degrade, what can be leached out of the system, how the leachates migrate and change the groundwater chemistry, and do these processes affect the long-term performance of the repository. Conceptual models are needed as a basis for quantitative assessment methods (see Section 3.2).

Closer to the surface, the long-term performance of the closure becomes more complex, in the sense of accounting for the changes in the surrounding rock and the variability in closure materials, and because external processes, such as freezing and thawing, glaciations, erosion etc. have more likely impact during the assessment time frame. On the other hand, the requirements can be less stringent closer to the surface in the sense that a localised loss of closure performance does not necessarily affect the repository at depth. In this context, a more qualitative assessment and the use of geological and anthropogenic analogues becomes more relevant and a more qualitative assessment can be seen as sufficient.

Considering the long-term evolution of closure during and beyond the next glacial cycle, geological evidence, i.e. natural analogues, is the only way to observe safety-relevant processes in the relevant time scales.

2.3 Processes affecting the near field

The main safety function of the closure is to support the performance of the repository system. Thus, many processes occurring locally or only in the upper parts of the closure system do not necessarily have any effect on the overall performance of the repository. Some processes, however, can have some effects on the near-field performance if they are related to interactions between closure materials and near-field components (backfill, buffer and canister) or if they affect the radionuclide transport in the system.

One example of these is cement degradation and formation of a high pH plume that can react with the backfill and bentonite buffer (e.g. REF). A quantitative assessment is needed for processes that have the potential to perturb the performance of the barriers system, i.e. rock, backfill, buffer and canister. It is also of use for developing the design specifications, by providing information on the amounts of potentially harmful substances that can be allowed in the repository closure.

The interaction between the deposition tunnel backfill and plug and the closure in the central tunnels can be studied through the PA analyses. This analysis can give feedback to the design of the closure central tunnel backfill.

2.4 The performance assessment of closure

How performance targets are then met during the repository evolution is assessed in the performance assessment report along with the formulation of scenarios to be analysed to assess the impact of uncertainties. In the TURVA-2012 safety case, submitted in support for the construction license application, closure performance was assessed quantitatively in relation to its effects on the hydrogeological evolution of the geosphere as well as with respect of the long-term effects of the cement degradation on clay-based materials (i.e. alkaline plume from cement leachates reacting with bentonite) (Posiva 2013a).

The approach for assessing the closure performance will be updated from the TURVA-2012 safety case including assessments of quantitative and qualitative nature. Updating discussion and new modelling reflect the updates in the initial state of the repository system.

The modelling of the hydrogeological evolution of the Olkiluoto site forms a major part of the performance assessment work. It provides information of the flow routes within the system than can be used also in material transport assessment for closure (e.g. alkaline plume), it also provides means of estimating transport paths for the radionuclide release calculations. To assess closure’s significance/uncertainties in the overall system performance, closure needs to be included in the models. This is done by using different hydraulic conductivities for the closure sections at different depths within the models. This has been included already in the TURVA-2012 analysis, and in the modelling updates a similar approach will be included.

2.5 Complementary considerations

The Complementary Considerations report will support the performance assessment. Processes related to closure were also discussed in qualitative level in Complementary Considerations (Posiva 2012b) reports. While central tunnel backfilling will be quite similar to that of deposition tunnels and the geological context is also relatively similar, especially in the upper parts of the repository materials and processes can be discussed in more qualitative way. The processes included in CC especially in relation with depth consider behaviour of plugs low-pH and OPC, behaviour of mixed crushed rock/clay materials, behaviour of rock based backfills etc. All these are discussed in relation to their installation depth and hence, considering effects of groundwater composition changes at relevant depth range, the expected extent of external processes (e.g. permafrost). Also erosion is included in discussion of closure's very long-term evolution (100 000 to beyond 1 Ma).

3 Summary

Providing a complete enough assessment for closure in Posiva's next safety case requires careful balancing between a sufficient level of detail for the design and the necessary information to assess whether the performance targets are met during the repository evolution. Both quantitative and qualitative assessments are needed to cover the essential parts of the safety case that involves closure:

- Assessing the performance of the closure also in relation to depth and related requirements
- Understanding of the behaviour of the closure during the whole 1Ma time frame and beyond
- Understanding the extent of closure near-field interaction and its long term implications
- Understanding of the general significance of the closure on the overall repository performance

The safety case methodology will present the information and assessment results in the context of performance assessment and complementary considerations. These two reports will describe the essential knowledge and assessment results. To some extent, it can be said that quantitative analyses are mostly provided within the performance assessment and qualitative analyses in complementary considerations. A report, Initial state, is planned to describe the design as installed and related potential deviations. Requirements for the closure will be described in the design basis report. Following the methodology presented in this paper, the assessment of the closure performance in the safety case will provide the level of detail needed for the operational license application as well as important feedback for future optimisations of the closure design.

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Posiva 2012. Safety case for the disposal of spent nuclear fuel at Olkiluoto – Description of the Disposal System 2012. Eurajoki, Finland: Posiva Oy. POSIVA 2012-05. 166 p. ISBN 978-951-652-186-5.

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Towards Robust Models of Well Seals and Plugs in CO_2 Storage Sites

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Underground storage of CO_2, captured at fossil fuel power stations and certain large industrial point sources, is widely proposed as a transitional technology for mitigating climate change due to anthropogenic CO_2 emissions. The greatest long-term risk is often assessed to be potential leakage from abandoned wells. Cement is the most common material used to plug such wells during abandonment. It is therefore necessary to assess how this material will behave in the presence of CO_2 and very saline formation water (brine), which is common in many potential CO_2 storage reservoirs. However, well cement behaviour under such conditions cannot be predicted reliably using conventional geochemical models. The reason is that these models calculate the activity coefficients of aqueous species using equations such as the Davies equation that are inappropriate for brines. To produce a more reliable model of cement well plugs in the presence of CO_2-charged brine, a fully-coupled model was developed that calculated activity coefficients using the "Pitzer" approach, which is appropriate for high ionic strength solutions. The models reproduced the main alteration features of well cement cores that had been in contact with CO_2-charged brine for c.30 years. The models also demonstrated that the cement's porosity would be sealed by amorphous silica and calcite after c.100 years, preventing significant further reaction. The results are consistent with hydrocarbon industry experience that suggests the biggest potential limitation on the effectiveness of any given cement well plug will not be chemical degradation, but rather physical defects associated with its emplacement. However, the geochemical alteration of different cements cannot be assumed to be identical. Specific applications of models like the one presented here are needed to help to support claims of long-term performance of different cement materials that might be used in well seals.

1. Introduction

Underground storage of CO_2, captured at fossil fuel power stations and certain large industrial point sources such as cement works and steel works, is widely proposed as a transitional technology for mitigating climate change due to anthropogenic CO_2 emissions. Frequently, the greatest assessed CO_2 long-term leakage risks from a proposed storage site arise from abandoned wells. At a properly selected and appropriately operated site these risks are low, but nevertheless confidence needs to be built that seals and plugs in wells will not degrade significantly over time. Long-term evolution models of sealing materials are therefore needed. The timescales are not precisely defined, but need to cover the period for which CO_2 must be isolated from the atmosphere to mitigate climate change. This period depends upon the residence time of CO_2 in the atmosphere, which is uncertain; published estimates range from a few years to several hundred years. However, the IPCC 5th Assessment Report (IPCC, 2015) states that between 15% and 40% of anthropogenic CO_2 emissions until 2100 will remain in the atmosphere after 1000 years. Furthermore, the European Commission's Carbon Capture and Storage (CCS) Directive (Council Directive (EC) 2009/31/EC) states that CO_2 must be contained "permanently". Clearly the evolution of well seals and plugs must be assessed for timescales of thousands of years, much longer than the periods of a few hundred years normally considered by the hydrocarbon industry when abandoning wells. In most well abandonment concepts for CO_2 storage, seals and plugs are composed of cement (usually Class G or H API) and it is necessary to evaluate the evolution of this material in the presence of CO_2-saturated water. However, when doing so a major challenge is that well cement behaviour in the presence of CO_2-charged brines cannot be predicted reliably using conventional geochemical models. The reason is that these models calculate the activity coefficients of aqueous species using equations such as the Davies equation that are appropriate only for low ionic strength solutions and not for brines. The work reported here aimed to address this limitation by developing robust fully-coupled models of reactions between cement and CO_2-charged brine that employ the “Pitzer approach” (Pitzer, 1987) to calculate activity coefficients of aqueous species.

2. Well Plugging and Abandonment Methods

In most concepts for underground storage of CO_2, supercritical dry CO_2 will be injected via one or more wells that are sited and / or orientated to prevent subsequent post-abandonment leakage of CO_2 through them. For example, injection wells may be located down-dip from the high-point of a storage reservoir, so that the injected CO_2 will move laterally away from the injection point, as it ascends due to its buoyancy (Figure 2-1). Thus, in the long-term such injection wells will not contact CO_2 or CO_2-charged water. In many areas that may be considered for a CO_2 store the potential leakage pathways of greatest concern are abandoned wells that may be contacted by the CO_2, after the CO_2 has attained its final location within the reservoir (Figure 2-1). Such wells are likely to be most common where a depleted hydrocarbon reservoir is to be used as the CO_2 store.

Initially, stored CO_2 can interact only with the lower end of the deepest cement plug in a well, unless there are permeable pathways such as fractures that conduct CO_2 or CO_2-charged brine through the cement (Figure 2-1).

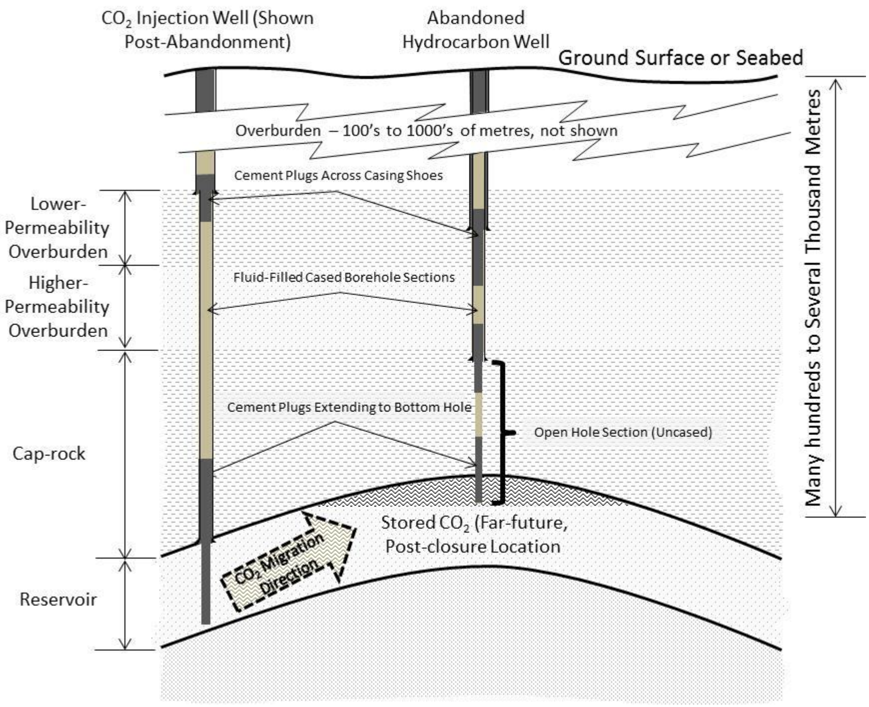

Figure 2-1. Schematic illustration of a CO_2 storage site showing two wells with different plug/seal designs.

3. Modelling Approach

Quintessa's QPAC software (Quintessa, 2013) was used to develop fully coupled 1-D chemical-transport models in which cement was exposed to CO_2-charged water. Alternative model cases were designed to determine the significance of uncertainties in thermodynamic and kinetic data.

Cement evolution was simulated using an ideal solid-solution model for C-S-H gel described by Kulik and Kersten (2001). Equilibrium constants were calculated for hydrolysis reactions involving the C-S-H gel over temperatures between 0°C and 100 °C. These calculations assumed that the gel is a solid solution of jennite-like and tobermorite-like end-members with compositions $(CaO)_{1.67}(SiO_2)(H_2O)_{2.1}$ and $(CaO)_{0.83}(SiO_2)(H_2O)_{1.3}$ respectively. Solid phase data were taken from Lothenbach et al (2008) and aqueous species data were taken from SUPCRT92 (dprons96.dat; Johnson et al., 1992). Equilibrium constants for other solid phase hydrolysis reactions were taken from the Geochemist's Workbench database "thermo.com.v8.r6+.dat" (Bethke, 2008).

Transition State Theory (Aagaard and Helgeson,1982; Palandri and Kharaka 2004) was used to model solid phase dissolution/precipitation kinetics, according to:

$$\frac{ds}{dt} = \left(k.A(H^+)^{n_1} + k.A + k.A(OH^-)^{n_2} + k.A(P_{CO_2})^{n_3}\right)\left(1 - \frac{Q}{K}\right)$$

where: s (mol) is the quantity of a solid, t is time (s), k is the rate constant (mol m^{-2} s^{-1}), A is the evolving reactive surface area of the solid (m^2 – calculated from the mineral abundance and its specific surface area), $n_{1,2,3}$ are dimensionless constants that determine the dependence of the reaction rate on the acidity/alkalinity/carbonate content of the fluid, Q is the ion activity product and K is the equilibrium constant for mineral dissolution (Q and K both being dimensionless). For calcite, kinetic data were taken from Palandri and Kharaka (2004). SiO_2(am) was assigned a fixed "rapid rate" k value of 10^{-3} mol m^{-2} s^{-1}. As no reliable published dissolution rates exist for C-S-H gel and $Ca(OH)_2$, these were determined by calibration against laboratory data, as described below.

The model was used initially to simulate published results from 9-day long laboratory experiments that investigated reactions between CO_2-charged water and cement (Kutchko et al., 2007). These experiments used water with an ionic strength of c.0.2 and hence activity coefficients could be calculated using the Davies equation, which is considered reliable to ionic strengths of c. 0.5 (Bethke, 2008). The models employed the "llnl.dat" thermodynamic database, which is distributed with PHREEQC (Parkhurst et al., 1999) and is derived from the Geochemist's Workbench database ""thermo.com.v8.r6+.dat". The CO_2-rich water composition used by the QPAC model was calculated using PHREEQC (Parkhurst and Appelo, 1999), taking as input the water composition reported by Kutchko et al. (2007) , the CO_2 concentration being fixed by its solubility, as determined using the equations of Duan and Sun (2003) and Duan et al. (2006). The water was calculated to have a dissolved C concentration of 1.357 mol kg^{-1}, ionic strength of 0.17 and pH of 3. Diffusion coefficients and kinetic parameters were adjusted until the model outputs matched the experimental observations closely, gaving an effective diffusion coefficient of 1.35 x 10^{-12} ms^{-2} for the cement and a reaction rate constant of 1 x 10^{-9} mol m^{-2} s^{-1} for C-S-H gel and portlandite.

After values for diffusion coefficients and kinetic parameters had been established, the model was used to simulate observed cement alteration in a well that had been used for CO_2-enhanced oil recovery (CO_2-EOR) in Scurry Area Canyon Reef Operators (SACROC) oilfield in Texas (Carey et al., 2007; Figure 3-1). Here, well casing cement (thought to be API Class A), had been exposed to CO_2-rich brine during EOR for >30 years, at a temperature of c.50 °C. Carey et al. (2007) reported observations on steel casing, cement and shale wall rock samples from between 4 m and 6 m above the contact of the limestone oil reservoir with the shale caprock. They found that the cement was carbonated for between 1 mm and 10 mm from both the casing-cement contact and the wallrock-cement contact (Along section A-B in Figure 3-1). These observations imply an alteration rate of up to 0.33 mm yr^{-1}.

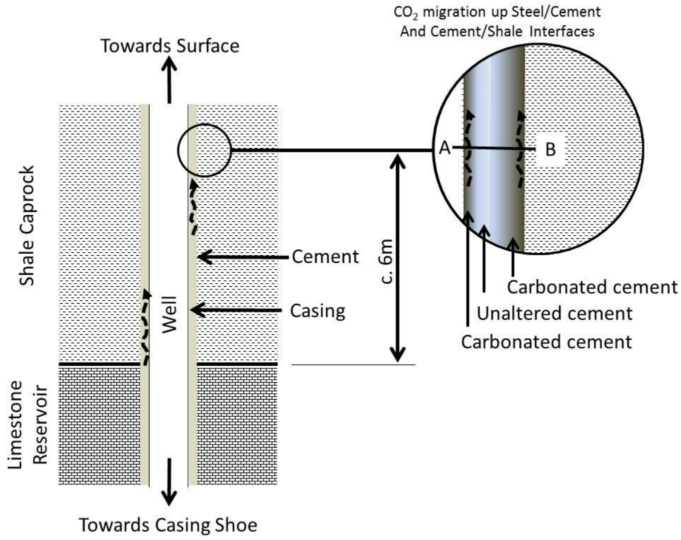

Figure 3-1. Schematic illustration of the SACROC situation, as described in Carey et al. (2007).

Again the CO_2-rich water composition used by the QPAC model was calculated using PHREEQC (Parkhurst and Appelo, 1999) and the water compositions given by Carey et al. (2007), the CO_2 concentration being solubility-limited, as determined using the equations of Duan and Sun (2003) and Duan et al. (2006). The water was calculated to contain 0.9 mol kg^{-1} dissolved C and to have ionic strength of 1.87 and pH of 4.5. Aqueous activity coefficients were calculated by the "Pitzer" approach, using the thermodynamic database "data0.ypf.R2" developed by Sandia National Laboratories, which is reliable for Na-Cl dominated water to ionic strengths >10 (USDOE, 2007).

4. Results

The results from the simulations of the SACROC site are summarized in Figure 4-1 and Figure 4-2.

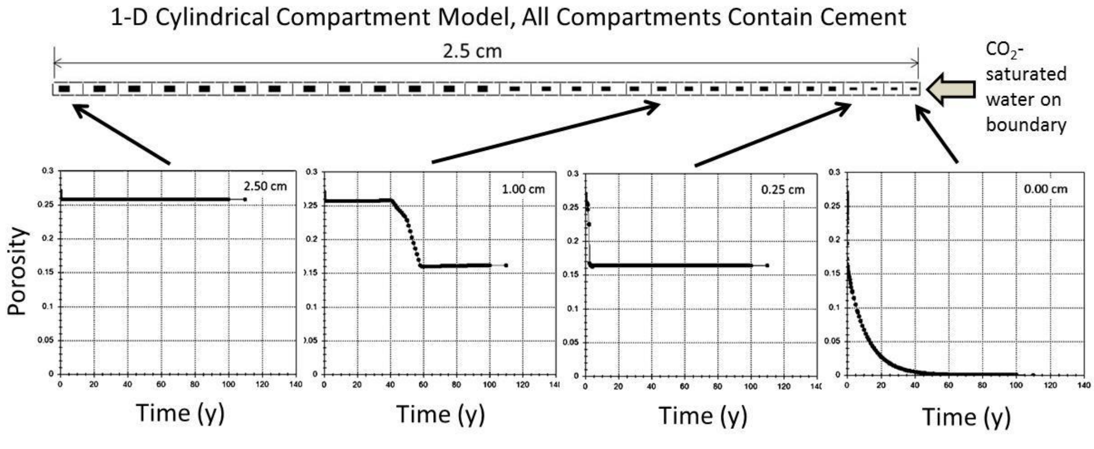

Figure 4-1. Model geometry (above) and output temporal variations in cement porosity(below).

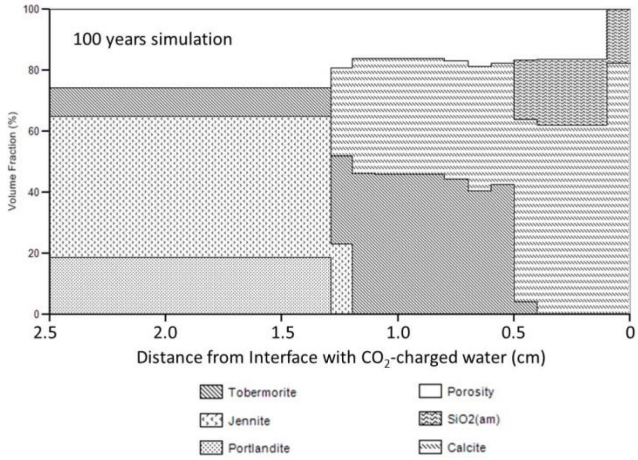

Figure 4-2. Modelled spatial distribution of primary and secondary phases in the cement after 100 years of exposure to CO_2-saturated brine at 50 °C.

Cement porosity was completely sealed near the interface between the cement and the CO_2-charged brine after 100 years, isolating the remaining cement and causing reactions in it to effectively cease. After 30 years of simulation (not illustrated), 0.9 cm of cement had been carbonated. This alteration rate is 0.3 mm y^{-1} and is comparable to the observed rate of up to 0.33 mm y^{-1} (Carey et al., 2007). After 100 years of reaction the depth of simulated cement carbonation was about 1.25 cm (Figure 4-2), giving an average alteration rate of 0.125 mm y^{-1}. Thus, the results show a gradual slowing of the cement carbonation rate over 100 years due to pore space clogging during progressive reaction.

5. Discussion and Conclusions

On theoretical grounds robust models of long-term cement evolution in the presence of brines should use the "Pitzer" approach for calculating the activity coefficients of aqueous species, rather than the "conventional" Davies equation or similar equations. However, available thermodynamic databases to support the "Pitzer" approach are more limited, in terms of both numbers of species and applicable temperature range, than thermodynamic databases that support the "conventional" approaches. Nevertheless, by simplifying the modelled representation of a real system it has been possible to develop a fully-coupled model of interactions between cement and CO_2-saturated brine that can match the main features of experimental and field observations.

The model has been used to predict cement behaviour in the presence of CO_2-charged brine over longer timescales (to c. 100 years) than those of laboratory experiments or field experience. This prediction suggests that the extent of cement alteration by CO_2-charged brine would be spatially limited to within a few centimetres of the cement-brine contact because the reactions that occur seal the cement's porosity. Due to this sealing the reaction rate becomes very small after about 100 years. The location of cement alteration several metres above the reservoir-caprock contact at the SACROC site (Carey et al., 2007; Figure 4-1) therefore implies that CO_2-charged brine ascended along physical defects in the cement, rather than through the cement's matrix. Possibly these defects occurred between the cement and the casing and between the cement and the shale wallrock.

The simulated temperatures were much lower than those of many reservoirs that might be considered in future for CO_2 storage; temperatures of over 100 °C are likely to be common. There are uncertainties about the physico-chemical evolution of cements in the presence of CO_2 at these high temperatures and in the presence of brines. Chemical processes alone will probably not compromise the sealing performance of cement plugs, but if there is brittle deformation of the plug, flow pathways for CO_2 might be created. The coupling between physical and chemical properties of cementitious plugs therefore requires further investigation.

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10.DOPAS 2016 Seminar Session 6

Session 6 examined topics related to training, information dissemination and regulatory supervision of plugs and seals. In addition, questions related to the lessons learned were collected via Panel discussion, and where DOPAS Experiment leaders were addressing the questions of the attendees submitted via the message wall during the seminar.

Chair: Erika Holt is program manager for Safe and Sustainable Nuclear Energy at VTT, Finland. She has 20 years of research experience, with a PhD in Civil Engineering from the University of Washington (2001, Seattle, USA). While at VTT she has been the leader of a 30 person research team on topics related to materials and infrastructure, especially for waste management applications. During DOPAS, she was the Project Manager of Posiva's POPLU Project.

Co-chair: Frédéric Bernier is Performance Assessment/Safety Assessment Expert and works at the Belgian regulator FANC (Federal Agency for Nuclear Control) and since 2007 has been in charge of geological disposal. He has worked at the Belgian research organisation SCK.CEN since 1992. First he worked with thermo-hydro-mechanical aspects in disposal, in the Belgian HADES underground laboratory since its construction e.g. as the manager of the PRACLAY heater test and in shaft sealing in-situ experiment, and then as scientific manager of EURIDICE consortium. He has also coordinated and worked with several Euratom projects related to the use of clay materials for disposal and participated in international working groups (at IAEA), steering committees and peer reviews e.g. of the Finnish Radiation and Nuclear Safety Authority STUK. Mr Bernier was an independent expert in the DOPAS expert elicitation, too.

Session 6 Schedule and direct links to the DOPAS 2016 Session 6 presentations:

1510-1530	DOPAS training workshop 2015	Marjatta Palmu[1] and Radek Vašíček[2] *[1]Posiva Oy, Finland* *[2]CTU, Czech Republic*
http://www.posiva.fi/files/4171/6.1_S6_Palmu_et_Vasicek_DOPAS_TWS_Seminar2016_final.pdf		
1530-1550	Regulatory point of view on the demonstration of the feasibility of plugs and seals for the final repository of radioactive nuclear waste	Pekka Välikangas *Radiation and Nuclear Safety Authority (STUK), 11.Finland*
http://www.posiva.fi/files/4172/6.2_Valikangas_DOPAS_20160526_Regulatory_point_of_view.pdf		
1550-1630	Current status of repository plugging and sealing and remaining technical and operational issues (DOPAS Experiments)	Panel session facilitated by Erika Holt[1], with an introduction by Matt White[2], followed by DOPAS Experiment leaders: Régis Foin[3], Jiri Svoboda[4], Pär Grahm[5], Petri Koho[6] *[1]VTT Technical Research Centre of Finland Oy, Finland* *[2]Galson Sciences Limited, United Kingdom*

		[3]Andra,France, *[4]Czech Technical University, Czech Republic* *[5]Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden* *[6]Posiva Oy, Finland*
http://www.posiva.fi/files/4173/6.3_-_ErikaHOLT_Panel_Q_A.pdf http://www.posiva.fi/files/4174/6.3_Matt_Panel_Introduction_White.pdf http://www.posiva.fi/files/4176/EXPERIMENT_SLIDE_Final.pdf		
1630-1650	Rapporteur summary	Pierre Berest *Ecole Polytechnique, Palaiseau,, France*
http://www.posiva.fi/files/4177/6.4_Expose_DOPAS.pdf		
1650-1700	Closing remarks	Johanna Hansen *Posiva Oy, Finland*

PANEL DISCUSSION QUESTIONS

(Summarized from message wall, by Erika Holt & Marjatta Palmu, 26.5.2016 at 13.30)

- **EU Project objectives:**
  - Where has cooperation BETWEEN national demos of DOPAS influenced others demos DURING the project? Going forward in programs from OTHERS?
- **DEMOS vs Actual Repository Plugs:**
  - Besides monitoring, what is different in DOPAS demos compared to actual repository plugs?
  - So far, plugging development seems technical. How much attention is paid to economic considerations for all aspects (concept, materials, construction, method statements, etc)?
- **Modeling:**
  - Germany/Oliver: How has formation of Brucite (or other sedimentary processes) been taken into account in modeling?
  - What constitutive model used for Rock salt with FLAC3D?
- **Requirements:**
  - Is it necessary to ensure strict watertightness of plugs used for functionality before closure?
- **Materials/Tunnel:**
  - How well have partners justified allowed tolerances for design/acceptance criteria (as needed for regulatory/compliance verification)?
  - If the slot excavation has sharp edges – will it impact grouting performance?
  - Has there been work on optimal size/shape of manufactured pellets?
  - Posiva: Why does your foreign materials reject SP chemicals (i.e. Glenium) yet allow organics associated with fly ash?
  - UJV: What is the justification for steel canisters in CZ repository?
  - ANDRA: What type of plug will be constructed for CIGEO demo?

  - POPLU/DOMPLU – having similar concrete, what were justifications for reinforced vs non-reinforced?
- **Future:**
  - *SKB (RWM?): Estimated cost and schedule to build (mass produce) a plug?*
  - How much have these demos actually impacted or given feedback to design (iteration) changes as you move forward?
  - What was learned from experiments that influences future information to your regulatory authorities?
  - What is the greatest impact from experiments towards next phase of your program?
  - What would you do differently if starting again?
  - Where would you monitor actual repository, considering these were experiments only?

OTHER (probably not to address, due to time constraint)

- **Dixon/Canada:**
  - Was TSX prepared with contact grouting tubes before casting?
  - Does ESP include conductive features at fracture locations on both sides?

Figure 10-1. DOPAS Experiment leaders in panel Session

Translating the experience from full-scale plugs and seals into a comprehensive DOPAS TRAINING WORKSHOP 2015

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ABSTRACT

The DOPAS project includes a component of knowledge transfer that was carried out in several ways during the project like in this seminar. One means was the creation and implementation of the DOPAS training workshop in 2015. Other means include also the three staff exchange programmes that took place to the FSS experiment in France, to the EPSP experiment in Czech Republic and to POPLU experiment in Finland. In addition, the project itself has benefited from the knowledge transfer from the experience waste management experts who have contributed to the review work of the project deliverables with the means of an expert elicitation process. A five-day week training workshop was carried out in September 2015 in the Czech Republic. The training planning was based on four major learning units and related learning outcomes including the provision of a full learning cycle with both theoretical and hands-on application of the tasks needed to plan, to construct, and to monitor a full-scale in-situ experiment. The trainers were mainly the experiment and work package leaders of the project from eight partner organisations. The curriculum followed the content of the DOPAS project plan starting from requirements and finishing with the technical feasibility considerations related to plugs and seals giving the participants an opportunity to construct and reflect on their own country's approach in contrast to the DOPAS approaches.

The training workshop was run with great success and very favourable replies were received from the participants and from the tutors to the extensive feedback collected.

1. Introduction to the context of the training workshop

The DOPAS project carried out the full-scale demonstration experiments on the plugs and seals needed for the geological disposal facilities and the experiences were used to produce a 5-Day Training Workshop on the Role of Full-scale Experiments on Plugs and Seals in Demonstrating Safety and Performance of Geological Disposal. This activity was included into the DOPAS WP7 as a part of the knowledge transfer and experience dissemination activities of the project for technical and scientific audiences, mainly young scientists, professionals and postgraduates in geological disposal.

This DOPAS activity had the objective to add to the scientific integration of the results and lessons learned and to share these by training of students and engineers from the EU

Member States. Further, the training was targeted for participants outside the project consortium and it was intended to capture all the stages of the DOPAS work plan. An additional objective was also to define the training so that at a later stage the recognition of the learning outcomes from the training workshop could take place e.g. according to using the ECVET tools (5).

The training was designed and implemented in September 2015 after the project had been running around three years. This enabled a training design that was based on the project's original conceptual framework and at the same time, it exploited the lessons learned during the three years of implementing the experiments. The project and the training workshop started from the requirements, safety functions, and constraints of plugs and seals leading into the implementation of full-scale construction of monitored repository plugs and the development shaft sealing components. The training workshop was designed to provide the participants a full learning/action cycle[1] including both theoretical knowledge and practical skills acquired in team work and in an underground training facility environment, the Josef Underground Laboratory in Czech Republic, at the Czech Technical University in Prague and at UJV Rez, a. s. The trainers for the workshop came from eight project partner organizations sharing the experience from all of the five DOPAS experiments: FSS in France, EPSP in Czech Republic, DOMPLU in Sweden, POPLU in Finland and ELSA preparatory experiments from Germany.

The training process included the planning, implementation and assessment of the workshop that is reported as a part of the DOPAS project including the training materials that will be publicly available on the DOPAS website http://www.posiva.fi/en/dopas at the end of the project. The following chapters describe the content of these stages.

2. Planning for the DOPAS training workshop

The initial ideas for the DOPAS training workshop were produced in collaboration with Posiva Oy and the Czech Technical University's (CTU) Centre of Experimental Geotechnics in June 2013, when the location and the time for the training was agreed. The week in September scheduled for the training provided unhindered access for the trainees to the Josef Underground Laboratory and research centre. The other training locations were at the faculty of Civil Engineering at the CTU in Prague and at the UJV Rez, a. s. in the Czech Republic.

The detailed content planning for the training started in May 2015 together with the eight consortium members complemented. Four planning meetings were held using remote connections (teleconferencing and a video link) and two weeks prior the meeting a face-to-face material review meeting was held in Helsinki, Finland. The planning consortium consisted of Posiva, SKB, Andra, CTU, SURAO, RWM and GRS complemented with UJV Rez staff and with training materials from Nagra adding the ninth member to the planning group. The duration of the training workshop was fixed to five days. In addition to the planning group members, the practical implementation of the training workshop was carried out with the help of additional tutors and lecturers from the Czech Republic.

[1] see Kolb, Lewin, and Dewey (1984) later in the text

Planning group member	Organisation, country
Marjatta Palmu, task leader of the training workshop, WP6 leader of DOPAS	Posiva Oy, Finland
Radek Vašíček, DOPAS training workshop course leader	CTU, Czech Republic
Jacques Wendling, Performance assessment of Andra's programme	Andra, France
Régis Foin, FSS experiment leader	Andra, France
Jiri Svoboda, EPSP experiment leader	CTU, Czech Republic
Pär Grahm, DOMPLU experiment leader	SKB, Sweden
Petri Koho, POPLU experiment leader	Posiva Oy, Finland
Lucie Bělíčková, Prague and Rez organization	SURAO, Czech Republic
André Rübel, Safety and performance assessment, WP5 leader of DOPAS	GRS, Germany
Dean Gentles, Application of lessons to other waste management programmes, WP4 leader of DOPAS	RWM, Great Britain

Tab 1: Planning group of the DOPAS training workshop

The planning approach was based on producing a complete action cycle for the learners based on Kurt Lewin's concept (1) and on the philosophy of Dewey (2). This concept has been further applied to training and represented in Kolb's Learning cycle (2). This same concept was used as the basis of Deming's wheel PDSA[2] (3), too, well known to people engaged in quality management and the implementation of ISO 9000 based quality systems (4). The application of Kolb's cycle in learning can start at any point of the cycle as long as the whole cycle is included in the learning process. In addition to this guideline, the training emphasized the need to combine both theoretical and practical activities carried out in small groups. The purpose was to ensure that the participants could learn knowledge, skills and competences (KSC) during the process. In the same way, the learning outcomes were defined by setting up the training from four main learning units following the ECVET (5) approach.

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

The expected Learning Outcomes (LO) for the participants were

- To understand the process/es of designing a full-scale experiment from a set of requirements related to the performance of the safety function/s of a plug or a seal as a repository component in geological disposal.
- To be able to contrast the differences of such processes resulting from the different

[2] "Plan, Do, Study Act" cycle

boundary conditions e.g. from the host rock environments (clay, crystalline rock, and salt), the experimental settings (above ground, underground experimental facilities vs. real repository conditions) and other site and disposal concept specific features.

- To comprehend the linking of different experiment project's related subprojects and tasks and their inputs and outputs as a part of the experiment implementation.
- To acquire hands-on experiences in experimenting with materials' testing and monitoring techniques needed in an experiment, and
- To know how the individual experiments and their outputs contribute to the overall demonstration and demonstration programmes for safety of the waste management programmes at the different stages of repository development.

The training design included four main Learning Units (LU) consisting of a total of 10 topics that were related to the desired Learning Outcomes (LO):

Learning Unit 1: From requirements to the design basis of plugs and seals (DAY 1) including
Understanding requirements management and their application for plugs and seals design basis

- The purpose of plugs and seals in clay
- The purpose of plugs and seals in crystalline rock
- Requirements - understanding and applying them (sources, requirements as a system)

The Design Basis development work flow for plugs and seals - Application of requirements management system to plugs and seals and developing a design basis from them.

- Developing a design basis for an experiment
- Case Example of the Czech experiment EPSP
- Scoping the DOMPLU experiment. Moving from the initial design to an experiment in place including Exercise 1

Learning Unit 2: Preparation of an in-situ or full-scale plug or sealing experiment (DAY 2)
How to come up with a coherent demonstration program for plugs and seals?

- Theoretical basis to Andra's iterative safety assessment process and the latest safety assessment round
- Actual case example about the last round of safety assessment iteration in Andra's demonstrator programme in clay (FSS) - Explicit description of the last iteration cycle

The role of instrumentation and monitoring in an experiment including the Exercise 2 (sensors, their installation and analysis of results)
Monitoring for performance assessment of experiment components (Thermal processes, Exercise 2 continuation) (DAY4)

Learning Unit 3: Design of a seal for an experiment/ demonstrator within the broader context of RD&D programmes (DAY 3 - DAY 4)
What is the state of the art in the demonstrator (RD&D) programs today?

- Andra's scientific programme and its current state. The main questions replied to for the next safety assessment report (DAC[3] 2017) and after the submission of DAC?
- Plugs as a part of the demonstration programmes in Nordic countries (YJH[4] and FUD and in the stages of licensing) - including alternatives

Behaviour of plug components and materials

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[3] DAC = Demande d'Autorisation de Construction French construction license.
[4] YJH = 3 year Finnish R&D programme plan, FUD = 3 year Swedish R&D programme plan for nuclear waste management

- The use of individual tests to complement existing material and process knowledge (case of REM[5] metric experiment)
- Instructions for laboratory Exercises 3-4 on material behaviour at UJV Rez a.s.

Introduction to Safety Assessment and integration of the experimental work and process modelling in the safety assessment/ safety case.

Learning Unit 4: Construction Feasibility of a plugging experiment (DAY 4 and DAY 5)
Practical underground work concerns in setting up an in-situ or full-scale experiment

- Risk management for large-scale experiments and work underground
- Case example of POPLU experiment (recipe development, method tests and casting, start slot location + RSC[6] and design; moving into real repository construction, as built vs. design) and related exercise on identifying and prioritizing risks for full-scale experiments
- Feasibility of a seal in a clay rich host environment. How to adapt the technological process including alternative concept/s
- Working methods underground and for experiments
- Lessons learned from the experiments until today - Panel on experiences, constraints and lessons learned

How to further apply the lessons learned for the future

- The use the DOPAS experiences in a waste management programme not yet in the demonstration stage or without a site - Case of RWM
- Preparing for ELSA experiment.

The different learning units were tied together with more general activities like general presentations on DOPAS, Josef facilities and on the Czech geological disposal programme. The planning group members took turns in chairing the different training days during the week and at the same time triggered discussion in the training group on the topics at hand. The planned exercises included group work on experiment project management, risks, hands-on production and installation of sensors into the underground facility, handling and interpretation of the measurement data, laboratory tests related to cement bentonite interaction and uni-axial testing on material samples for identifying strength and failure mechanisms.

During the last day, the participants were given an opportunity to interview the tutors in a closing panel focusing on the lessons learned from the DOPAS experiments. In addition, the day included a self-assessment by the group on how they had attained their objectives for the training.

3 Implementation of the DOPAS training workshop

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

The participants came from Czech Republic (3 persons), Finland, Germany (2 persons), Great Britain, Hungary (3 persons), Poland, and Sweden. Four of the participants were

[5] REM = resaturation test related to the FSS experiment clay materials by Andra
[6] Rock Suitability Criteria

active students in the German and Czech universities, at the same time they were working at various organizations. Seven of the participants came from consulting or engineering organizations, two came from waste management organizations and the rest from an authority and research organizations and universities. All of the participants had a scientific or technical background, with most of them with a background in geotechnical engineering or geology.

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

The first training day took place in Prague at the CTU. The purpose of the day was to provide the training participants an orientation to the training topic and at the same time to get them acquainted with each others. The content focus was on the requirements and design basis of plugs and seals and on their purposes. The practical experiments included the presentation of the Czech and Swedish plug experiments, EPSP and DOMPLU. The introductory day's short exercises in pairs and small groups promoted the participants to get to know each other for supporting and open-minded cooperation during the workshop.

The second day continued at the Josef facilities with the presentations about the interactive process of safety assessment in the case of Andra and about the role of the FSS experiment in it. The training also included an introduction to the Josef facilities, the role of monitoring and instrumentation in the experiments, and a hands-on exercise in preparing thermal sensors and their installation into the Josef underground into the vicinity of the heater assigned for this exercise purpose. The data was then collected and interpreted during the fourth day when the training group returned to Josef again.

Fig 1. "Who has experience with soldering?" Day 2 practical exercise on sensor making in one of the groups.

Photos: Marjatta Palmu, Posiva Oy

Fig 2. "Let's put the sensors in place" at Josef Underground Laboratory.

The third day started at UJV Rez a.s., where practical works continued after the presentations about the French and Nordic research and development programmes where the experiments are on part of the planned work. The work continued at the UJV Rez laboratories with the practical exercises. After the laboratory exercises the group moved to the SURAO information centre in the centre of Prague. The focus was on the Czech siting programme and on stakeholder communication. The evening ended with a "movie night" and discussion related to the "Into eternity" documentary.

The fourth day took place in Josef again. The content focused on the general principles of safety assessment and on the technical feasibility of the plug and seal construction. Presentation of the POPLU, DOMPLU and FSS plugs' construction works were given and the participants worked on identifying the potential risks related to the experiments in the Nordic countries. The second part of the long day at Josef was spent in analyzing the sensor data from the sensors installed in the heated rock. Finally, the day was finished with a visit to the Josef cathedral with Czech music and the light show.

Last training day brought the group back to Prague, where the participants learned about the German ELSA experiment and related materials, about how RWM aims to use the lessons learned, and the experiments' lessons learned were summarized in a tutor panel. The afternoon was filled with the participant presentations on the outcomes of their exercises during the week. They received feedback from the various tutors on their findings. The groups sent their exercise reports to the tutors after the training course and were given a further evaluation of their work, too. The day and the official training course finished with the participants assessment on their attainment during the week. In practice, beautiful Prague saw still a group of enthusiastic training participants enjoying their last night in the golden city.

4 Assessment of the DOPAS training workshop

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

In the beginning of the workshop the participants set their own expectations and goals for the training (see ref. 6, p.4) and most of their objectives were achieved. In addition to the group assessment, the participants also gave their individual evaluation of the workshop on an evaluation form. The outcomes of the evaluation varied on a scale from 1-5 between from 4.3 to 4.8 on average on nine different evaluated items. Replies were received from all participants. The tutors made a similar evaluation independently and came to the same conclusion as the participants.

D - Demonstrative

O - Optimistic

P - Positive

A - Accurate

S - Serious

DOPAS Training Workshop 2015 as described by one of the participants.

Entering Josef cathedral. Photo: Marjatta Palmu

Fig 3. DOPAS Training Workshop 2015 participants and tutors on Day 4

The participants received a training workshop diploma with a recommendation letter from the workshop organizers supporting the recognition of the amount of work done in the workshop to equal four ECTS for academic studies.

The outcomes of the training workshop are to be documented using the ECVET approach in the form of KSC needed for each of the learning units and related learning outcomes before the end of the project. This documentation is intended to make it easier for any future users of the training material to apply it using the similar principles and approaches in their training.

5 Conclusions and acknowledgements

The workshop was successfully implemented and well received from both the participants and the tutors. The planning process also assisted in structuring the connections of the DOPAS work for the tutors engaged in the process and this contributed also directly to the planning of the expert elicitation of the DOPAS work package deliverables. Much work was done to produce the plan and to implement it. We hope that when the training workshop report comes out, also other trainers find the materials useful and use them in future training.

Defining and implementing the workshop content according to ECVET tools was beneficial for both – the participants and organizers - as this course provided first opportunity to experience and use the ECVET approach for many of them.

Special acknowledgements go to all the tutors and the members of the training workshop planning group and to Nagra contributing their materials for the training and to other DOPAS consortium members.

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7 DOPAS specific abbreviations

DOMPLU	Dome Plug deposition tunnel plug experiment carried out in Äspö Hard Rock Laboratory in Sweden by SKB in collaboration with Posiva
DOPAS	Full-scale Demonstration of Plugs and Seals, Euratom FP7 Framework project
EPSP	Experimental Pressure and Sealing Plug experiment in Josef Underground Laboratory in Czech Republic

FSS	Full-scale Seal experiment in St.Dizier France
POPLU	Posiva Plug wedge shaped deposition tunnel plug experiment in ONKALO underground rock characterization facility in Finland by Posiva in cooperation with SKB.
ELSA	Entwicklung von Schachtverschlusskonzepten (development of shaft closure concepts) related tests and future experiment in Germany

For further explanations please visit http://www.posiva.fi/en/dopas.

Regulatory point of view on the demonstration of the feasibility of plugs and seals for the final repository of radioactive nuclear waste

Pekka Välikangas[1], Rainer Laaksonen[2], Radiation and Nuclear Safety Authority (STUK), Finland

1. Section Head in Civil Engineering and Fire protection in Nuclear Reactor Regulation, MSc (Civ.eng.), 11 years in regulatory duty in STUK including development of inspection analogy between nuclear power plant and final repository of nuclear waste and before that 22 years in design duties in NPP and conventional power plant construction
2. Senior Inspector in Nuclear waste and material regulation, Lic. Sc. (Tech.), seven years in regulatory duty in STUK, working with buffer and backfill feasibility.

STUK - Radiation and Nuclear Safety Authority is a public authority operating under the Ministry of Health and Social Affairs of Finland. STUK's mission is to protect people, society, the environment and future generations from harmful effects of radiation. One of STUK's operational areas is to regulate and oversee principles of nuclear waste management and the final disposal of radioactive waste. STUK is giving safety requirements and guidance for nuclear power plants and nuclear facilities in YVL guides. YVL E.6 (Buildings and structures of a nuclear facility) is the closest radiation and nuclear safety guide related to plugs and seals, discussed in current DOPAS 2016 forum. YVL E.6 sets the requirements for construction materials, structures and structural systems in a nuclear facility starting from traditional and nuclear facility specific standards and accepted procedures point of views. Beyond standards and codes the guide also allows and if found necessary requires the use of mock-up tests to replace or compensate the standard and code specific approach concerning concrete and steel structures as well as composite steel-concrete structures.

Mock-up is presenting final approvable model solution for further construction. It is a combination of conventional design and construction part and part from extensive research, planning and testing done by the industry/licensee. Mock-up may be used for ensuring the design and production of materials, type of structures and structural systems. Mock-up should connect safety requirements to corresponding design criteria by solutions, tested according to design based approval criteria. A sequence of phases leading to "qualified" plug or seal structure can thus start from the R&D work including material tests, continuing through extensive design phase, small scale mock-up tests, preliminary demonstrations to full scale mock-up test and ending to conclusions of the plug or seal fulfilling design and safety criteria. STUK oversees the procedure in order to be capable to make corresponding structural and commissioning inspections. So far STUK has overseen and followed certain licensees' inspections of KBS-3V alternative of tunnel plug and seal (PoPlu). The basic goal is to inspect mock-ups in a similar way as final structures in order to pilot and train for final construction. Records from inspections are needed, if this testing and further mock-ups are utilized as parts in the final inspections proceeding to approved operating license application of a safety classified plug and seal structures.

Before sending to STUK, construction design documentation has to be checked and approved by the licensee including "summary of justifications" as required in YVL E.6, chapter 7.11. Then STUK can approve the documentation on which structural inspections are based. Commissioning inspections are based on quality control records collected from mock-up and final construction as well as on as-built documentation, which is a basis for further monitoring and maintenance program. More information about inspections are given in YVL E.6, chapter 9.

In addition to the general requirements for the mock-up as stated in YVL E.6, there is a multitude of requirements in STUK's YVL –guides that the licensee and it's subcontractors must be aware of and carry out operation accordingly. There are also requirements for the organizations and responsible personnel carrying out the various phases of this work; planning, constructing, testing and monitoring, date reduction and reporting. Since the tunnel plug and seal structures are very specialized in civil works domain it can be acknowledged that mock-ups can serve also as organization and personnel qualification function as well as on technical qualification issues.

12. DOPAS 2016 POSTER SESSION

Altogether 26 posters were visible at DOPAS 2016 Seminar exhibition area. The seminar sessions were in conjunction of the lunches and coffee breaks and worked as a space for discussions and networking for the attendees and the presenters. It was found a good idea to bring the different materials used in DOPAS experiments on site and to have the Experiment videos running during poster sessions.

Poster Session	Subject	Presenter
1	DOPAS Project	Johanna Hansen *Posiva, Finland*
http://www.posiva.fi/files/4503/Posiva_DOPAS_2016_general_poster_published.pdf		
2	DOPAS Design Basis Workflow for Plugs and Seals	Matt White and Simane Doudou [1]*Galson Sciences Limited, United Kingdom*
http://www.posiva.fi/files/4479/Galson_Sciences_Limited_Design_basis_of_plugs_and_seals_DOPAS_2016.pdf		
3	Current status and next five year plan of R&D activities of Mizunami Underground Research Laboratory	Shin-ichro Mikake[1], Teruki Iwatsuki[1], Hiroya Matsui[1] and Eiji Sasao[1] [1]*Japan Atomic Energy Agency, Japan*
http://www.posiva.fi/files/4475/JAEA_5_year_plan_for_Mizunami_DOPAS_2016.pdf		
4	A challenging environment for plug design: how can we seal a low-permeability fault core in granite	Kálmán Benedek[1], Péter Molnár[1], József Berta[1] [1]*Puram, Hungary*
http://www.posiva.fi/files/4486/PURAM_plug_design_DOPAS_2016.pdf		
4	Horizontal bentonite backfilling and concrete plug for the Full-Scale Emplacement (FE) experiment at the Mont Terri URL: requirements, design, instrumentation and emplacement	Benoit Garitte[1], Sven Köhler[1], Herwig R. Müller[1], Toshihiro Sakaki[1], Tobias Vogt[1], Hanspeter Weber[1], Martin Holl[2], Michael Plötze[3], Volker Wetzig[4], Moreno Tschudi[5], Heinz Jenni[6], Tim Vietor[1] Eric Carrera[7], Gerd Wieland[7], Sven Teodori[8], José-Luis García-Siñeriz Martínez[9], Frank Jacobs[10] [1]*National Cooperative for the Disposal of Radioactive Waste (Nagra), Switzerland* [2]*J.Rettenmaier & Söhne, Germany* [3]*ETH, Switzerland* [4]*VersuchsStollen Hagerbach, Switzerland* [5]*Belloli, Switzerland* [6]*Rowa, Switzerland* [7]*Amberg Engineering, Switzerland* [8]*ÅF-Consult, Switzerland* [9]*AITEMIN, Spain* [10]*TFB, Switzerland*

http://www.posiva.fi/files/4487/Nagra_FE_LUCOEX_Production_of_bentonite_based_backfill_materials_DOPAS_2016.pdf		
4	Investigation of chemical-hydraulic behaviour of cement based sealing materials in rock salt (DOPAS Project)	Kyra Jantschik[1], Helge C. Moog[1] *[1]Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) GmbH, Germany*
4	Investigation of hydro-mechanical behaviour of cement based sealing materials in rock salt (DOPAS Project)	Oliver Czaikowski[1], Klaus Wieczorek[1] *[1]Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Germany*
4	Hydro-mechanical behaviour of claystone-bentonite-mixture as sealing material (DOPAS Project)	Chun-Liang Zhang *Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Germany*
4/5	Outcomes of FSS, the Full Scale Seal Industrial Prototype for the Cigéo project (DOPAS Project)	Jean-Michel Bosgiraud[1], Régis Foin[1], Gilles Armand[1] *[1]Andra, France*
http://www.posiva.fi/files/4481/Andra_Outcome_of_FSS_DOPAS_2016.pdf		
4/5	REM (Resaturation Test at Metric Scale) setup and first results (DOPAS Project)	Nathalie Conil[1], Pasteau Antoine[1], Jean Talandier[1], Gilles Armand[1] *[1]Andra, France*
4	DOPAS EPSP Experiment (DOPAS Project)	Svoboda Jiří[1], Vašíček Radek[1], Markéta Dvořáková[2], Václava Havlová[3] *[1]CTU, Czech Republic* *[2]SÚRAO (Radioactive Waste Repository Authority), Czech Republic* *[3]ÚJV Řež, Czech Republic*
http://www.posiva.fi/files/4478/CTU_EPSP_Experiment_DOPAS_2016.pdf		
4	The Experimental Pressure and Sealing Plug (EPSP) – Improvement of the geotechnical properties of the rock mass (DOPAS Project)	Markéta Dvořáková[1], Irena Hanusová[1], Lucie Bělíčková[1] *[1]SÚRAO (Radioactive Waste Repository Authority), Czech Republic*
4	Physical interaction model and EPSP materials characterisation (DOPAS Project)	Petr Večerník[1*], Jenny Gondolli[1], Dagmar Trpkošová[1], Václava Havlová[1] *[1]ÚJV Řež, Czech Republic*
http://www.posiva.fi/files/4477/UJV_PIM_and_EPSP_characterisation_DOPAS_2016.pdf		
4	The laboratory models for EPSP experiment in DOPAS project - the saturation of bentonite pellets and bentonite powder (DOPAS Project)	Dagmar Trpkošová[1], Petr Večerník[1], Jenny Gondolli[1], Václava Havlová[1] *[1]ÚJV Řež, Czech Republic*
http://www.posiva.fi/files/4476/UJV_Laboratory_model_PHM_DOPAS_2016.pdf		
4/5	DOPAS EPSP Experiment Monitoring	Svoboda Jiří[1], Vašíček Radek[1], Šťástka Jiří[1], Smutek Jan[1] *[1]CTU, Czech Republic*
http://www.posiva.fi/files/4480/CTU_EPSP_Experiment_MONITORING_DOPAS_2016.pdf		
4/5	Full-scale test of Dome plug (DOMPLU) (DOPAS Project)	Pär Grahm[1], Mattias Åkesson[2] *[1] Swedish Nuclear Fuel and Waste Management Co, Sweden* *[2] Clay Technology AB, Sweden*
http://www.posiva.fi/files/4501/SKB_Domplu_full_scale_test_20160516_A0.pdf		

4	POPLU Requirements, Design and Construction (DOPAS Project)	Petri Koho, Petri Korkeakoski *Posiva, Finland*
4	POPLU instrumentation (DOPAS Project)	Edgar Bohner, *VTT Technical Research Centre of Finland Oy, Finland*
http://www.posiva.fi/files/4502/VTT_POPLU_instrumentation_17052016_FINAL.pdf		
5	POPLU Pressure testing and Performance (DOPAS Project)	Petri Korkeakoski[1], Petri Koho[1], Kimmo Kemppainen[1], Antti-Jussi Kylliäinen[1] *[1]Posiva Oy, Finland*
http://www.posiva.fi/files/4482/Posiva_POPLU_Pressure_Testing_and_Performance_DOPAS_2016.pdf		
4	Testing grouting and shotcrete materials	Paula Raivio, *Contesta, Finland*
4	Hydraulic Sealing Ability of Bentonite Pellet Filling at Small, Contact Apertures	Jari Martikainen[1], Tim Schatz[1], Kari Koskinen *[1]B+Tech, Finland* *[2]Posiva Oy, Finland*
http://www.posiva.fi/files/4484/BTECH_Gap_Sealing_Poster_DOPAS_2016.pdf		
4	KBS-3V emplacement tests in ONKALO	Keijo Haapala *Posiva Oy, Finland*
http://www.posiva.fi/files/4522/Posiva_LUCOEX_WP5_ASPO_2015_FINAL_Dopas_2016.pdf		
5	Testing the influence of bentonite sealing property for safety of deep geological repository	Dagmar Trpkošová[1*], Petr Večerník[1], Jenny Gondolli[1], Václava Havlová[1] *[1]ÚJV Řež, Czech Republic*
http://www.posiva.fi/files/4485/UJV_bentonite_sealing_property_for_safety_of_deep_geological_repository_DOPAS_2016.pdf		
4	Development of shaft sealing systems for HLW repositories in Germany	Michael Jobmann[1], Philipp Herold[1], Matthias Gruner[2], Wolfram Kudla[2] *[1]DBE TECHNOLOGY GmbH, Germany* *[2]Technische Universität Bergakademie Freiberg, Germany*
5	Compliance Assessment for plugs and seals in Germany	Michael Jobmann[1], Philippe Herold[1] *[1]DBE TECHNOLOGY GmbH, Germany*
5	Reactive transport modelling of bentonite shaft seals under hypersaline conditions	James Wilson[1], Steven Benbow[2], Richard Metcalfe[2], Helen Leung[3] *[1]Quintessa Limited, UK* *[2]Quintessa Limited, UK* *[3]Nuclear Waste Management Organization, Canada*
http://www.posiva.fi/files/4524/Quintessa_DOPAS_2016_ShaftSeal_v2.pdf		
5	Laboratory and numerical investigation of the hydro-mechanical behaviour of the Cobourg limestone	G. Su[1], S. Nguyen[1], Z. Li[1], M.H.B. Nasseri[2], R.P. Young[2] *[1]Canadian Nuclear Safety Commission, Canada* *[2]University of Toronto, Canada*
http://www.posiva.fi/files/4483/Canadian_nuclear_safety_commission_investigation_of_the_hydro_mechanical_response_of_the_Cobourg_limestone.pdf		

Experiment related demonstration materials labelled and exhibited during the poster sessions are listed below.

DOPAS Experiment 1 FSS (France)

1 Low pH concrete (normal vibrated)
2 Low pH self-compacting concrete
3 FSS filling material (blend of pellets 32 mm + crushed pellets' powder)
4 Bentonite powder made with crushed pellets
5 Bentonite Pellets (roller-compacted WH2 bentonite, 32 mm diameter)
6 Strain gauge embedded to concrete

DOPAS Experiment 2 EPSP (Czech Republic)

7 Mini EPSP
Showing examples of materials used for plug construction
8 Pellet sample 1

DOPAS Experiment 3 DOMPLU (Sweden)

9 Diamond-wire
(Used for sawing in crystalline rock)

DOPAS Experiment 4 POPLU (Finland)

10 DOPAS Experiment
11 Diamond-wire
12 Bentonite tape
(Used for sealing circumferential)
13 Bentonite powder (MX-80)
(Used to compact bentonite)
14 Bentonite Cebogel extruded pellets
(Used around blocks in backfill)
15 Compacted bentonite disk (MX-80)
(Similar to backfill block appearance)
16 Reinforcement steel bar
(Used for concrete plug reinforcement)
17 Low pH self-compacting concrete
(Cast in-place for plug)
18 Pellet sample 2
19 ONKALO rock sample

DOPAS Experiment 5 ELSA (Germany)

20 Compacted crushed rock salt (10x5x4 cm, including large salt grains)
21 Compacted crushed rock salt (10x5x4 cm, without large salt grains)
22 Rock salt (host rock) (Part of a drilled core of the salt host rock)
23 Crushed rock salt (salt grit)
(Used as backfill in the drifts of the repository and long-term sealing of the shaft)
24 Compacted salt grit
(Provides the long-term sealing of the repository in salt host rock)

25 Salt concrete
(Can be used in the shaft sealing system as material for one of the sealing elements)

26 Sorel concrete
(Can be used in the shaft sealing system as material for one of the sealing elements)

Figure 12-1. Poster session overview

Design Basis of Plugs and Seals: The DOPAS Design Basis Workflow

Matt White and Slimane Doudou

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Work Package 2 (WP2) of the DOPAS Project was focused on the development of the design basis for plugs and seals. Work on the design basis allowed assessment of current practice with regard to both the process used to develop and describe the design basis, and the content of the design basis of plugs and seals. The 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". This paper provides a description of the DOPAS Design Basis Workflow. The Workflow is structured to be consistent with the three broad design stages: conceptual design, basic design and detailed design. The key observations are that the requirements and design development processes are integrated and iterative, and that requirements are developed in parallel with designs rather than as a sequential process.

1 Introduction

Work Package 2 (WP2) of the DOPAS Project was focused on the development of the design basis for the plugs and seals. The work in WP2 was used to develop generic guidance on the development of the design basis in terms of a DOPAS Design Basis Workflow. This paper provides a description of this workflow and its components.

2 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. This definition is consistent with approaches to systems engineering and requirements management (e.g., NASA, 1995; and Robertson and Robertson, 1999). 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).

In DOPAS, the requirements contained in a design basis of plugs and seals are described in terms of the following generic hierarchy:

- Stakeholder requirements: These 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.
- System requirements: These are requirements on the disposal system that result from adoption of a specific conceptual design, i.e., the safety functions provided by the disposal

system and that elements that comprise the disposal system. For plugs and seals, therefore, system requirements are the safety functions provided by plugs/seals.

- Sub-system requirements: A list of the functions that the components of the selected plug/seal design must provide and the qualities that these components must have.
- Design requirements: Statements, usually expressed qualitatively, describing the qualities or performance objectives for plug/seal components.
- Design specifications: A list of quantitative statements describing the detailed requirements on plug/seal components (e.g., their thermal, hydraulic, mechanical, chemical and gas performance; 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.

3 The DOPAS Design Basis Workflow

Work on the design basis in the DOPAS Project has allowed assessment of current practice with regard to both the process used to develop and describe the design basis and the content of the design basis of plugs and seals. The design basis is developed in an iterative fashion with inputs from regulations, technology transfer, tests and full-scale demonstrations, and performance and safety assessments. The learning provided by WP2 has been used to describe a generic process for development of the design basis for plugs and seals called the "DOPAS Design Basis Workflow" (Figure 1). This Workflow is structured to be consistent with a design hierarchy consisting of conceptual, basic and detailed design stages (IAEA, 2001).

In the descriptions below, terms used in the Workflow are highlighted in ***bold italic*** font upon first use. These terms also defined in the glossary of the DOPAS WP2 summary report (White and Doudou, 2016).

3.1 Design Basis Development during 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 and/or 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.

The starting point for development of a design basis for a plug/seal conceptual design is a ***policy decision*** to manage radioactive waste through geological disposal. Following a national policy decision, ***stakeholder requirements*** that define what must be achieved by geological disposal are established. Stakeholder requirements include principles, regulations and criteria defined in regulatory guides and policy statements. In addition, stakeholder requirements could include specific approaches (e.g., a reversibility principle) that must be considered in the repository design.

Consideration of the stakeholder requirements, and the ***waste and host rock characteristics***, leads to the development of a ***safety concept*** upon which the disposal system requirements can be defined. The main functions of a disposal system are isolation and containment of the waste. These functions are provided by a combination of the geological barrier and the engineered barrier system. Elaboration of this safety concept allows parallel development of the ***system requirements***, including definition of ***plug/seal safety functions***.

Once the safety functions of the plug/seal have been defined, the conceptual design of the structure can be developed. This is typically progressed through consideration of a range of ***plug/seal***

conceptual design options. These design options would be identified through consideration of existing knowledge including ***design experience*** and general ***material understanding***. Development of the conceptual design options allows parallel development of ***sub-system requirements on plug/seal components***, i.e., elaboration of the role of each of the components in the design options of a plug/seal.

Consideration of the ***site environmental conditions*** in which the structure might have to perform, and conversion of these conditions into the ***loads*** that the structure might have to withstand will provide a basis for ***performance assessment of plugs and seals*** focused on the proposed conceptual design options. This performance assessment will take place through a programme of laboratory testing and computer modelling.

Evaluation of the outcome of the plug/seal performance assessment studies, through conduct of a ***compliance assessment***, allows the conceptual design options to be evaluated and a ***plug/seal conceptual design*** to be selected. At this early stage in design basis development, it is expected that the compliance assessment will consider a few key criteria in choosing between the design options. Once a plug/seal conceptual design has been selected and confirmed as appropriate using compliance assessment, the design can be documented. In parallel with the documentation of the conceptual design, ***preliminary design requirements*** can be elaborated. Preliminary design requirements are an initial set of qualitative statements describing the qualities or performance objectives for plug/seal components that will be tested in experiments. These will be identified through analysis of the performance assessment results during the compliance assessment, and by adding further detail to the sub-system requirements on plug/seal components.

3.2 Design Basis Development during 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.

The starting point for development of a design basis for a plug/seal basic design is the set of ***preliminary design requirements*** developed in parallel with the elaboration of the plug/seal conceptual design. ***Strategic preferences***, the results from ***materials research***, and ***technology transfer*** are considered during the development of a ***preliminary basic design*** based on the preliminary design requirements.

The key aspect of the basic design phase for plugs/seals, as undertaken within the DOPAS Project, is the use of full-scale testing as a means of further developing the design basis and the associated design. In order to conduct a full-scale experiment of the preliminary basic design, the requirements on the experiment need to be defined, and these requirements form a set of ***experiment design specifications*** (quantitative statements describing the detailed requirements on plug/seal components) that are developed in parallel with a set of ***working assumptions for the reference design specifications***. The working assumptions will form the basis for detailed design specifications produced as an output of this basic design development process taking advantage of the full-scale testing process. The elaboration of the experiment design specifications and the set of working assumptions for the reference design specifications is supported by the ***safety assessment*** calculations undertaken as part of the safety case, and by consideration of any ***operational constraints*** that affect how the plug/seal must be installed in the repository.

Following the elaboration of experiment design specifications, an ***experiment design*** can be developed. This will take account of ***experimental constraints*** and ***site-specific conditions*** encountered at the actual location of the experiment. Experimental constraints may result in changes to the experiment design compared to the reference design and may also impact the manner in which the experiment is undertaken.

After establishing an experiment design, ***a full-scale test*** may be undertaken. The outcomes of full-scale tests should be evaluated using a structured ***compliance assessment*** methodology. This would involve consideration of the full-scale test results on a requirement-by-requirement basis, and assessment of how closely the test met the specification. Full-scale testing also provides an opportunity for selection of the most appropriate design of plug/seal design through consideration of the ***most appropriate techniques*** applied in the test and the ***most appropriate performance*** for the design being tested.

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

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

3.3 Design Basis Development during Detailed Design

In a detailed design, the concept is presented in such detail that it can be constructed, i.e., it provides precise information on all aspects of the structure's components. The starting point for the detailed design development is the information from full-scale testing of the basic design and the set of ***detailed design specifications*** that describe the expected quantitative requirements on the design.

In order to convert the basic design into a detailed design that can be implemented in the repository, ***quality control procedures*** and ***construction procedures*** need to be written, and the design tested again (if required) to ensure that following these procedures will result in a plug/seal that meets the design specifications. Quality control procedures will define the manner in which the implementer will ensure that the plug/seal meets the design specifications within the given tolerances. This includes listing of the standards that will be followed during construction. Construction procedures will define the manner in which the plug/seal will be implemented. For example, these procedures will define the approach to excavation of the plug/seal location, mixing of concrete and the installation of the components of the plug/seal.

Elaboration of quality control and construction procedures is supported by the ***safety assessment*** calculations undertaken as part of the safety case and will take account of any ***operational constraints*** that affect how the plug/seal must be installed. These would be taken into account during the detailed design stage, and include any processes that respond to requirements from operational safety or other operational constraints including the feasible underground working methods in the limited dimensions of the underground space.

Elaboration of the quality control and construction procedures would provide the additional basis for developing a ***detailed design***. This design would be the basis for a ***commissioning test*** ahead of implementation (if required based on the technical outcome of previous full-scale tests). The results of the detailed design commissioning test will be checked by a final ***compliance assessment***.

Although it would be expected that the commissioning test would be mainly confirmatory, the compliance assessment will check that all of the design specifications in the requirements hierarchy are met, and may therefore lead to revisions in design specifications, quality control and construction procedures, or detailed design. Where these are minor, it would be expected that these can be implemented in the design basis without the need for a further iteration of the design cycle. In such a case, the detailed design specifications would be adopted (with necessary revisions) as the final design specification and the detailed design adopted as the final ***plug/seal detailed design*** (again with revisions identified through the full-scale test). Alternatively, major compliance issues may lead to a need for revision to the design specifications, quality control and construction procedures, and/or the detailed design, and further full-scale testing.

Major compliance issues could also lead to reconsideration and ***feedback to basic and/or conceptual design***, if the full-scale tests identified any fundamental issues with the design. Given the iterative nature of the development of the design basis as described above, in particular the inclusion of an optimisation step as part of the process for developing the basic design, it is unlikely that there would be a need to reconsider the basic and conceptual designs at the detailed design stage.

4 Conclusions

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

Although the DOPAS Design Basis Workflow is based on the design basis work undertaken for plugs and seals within the DOPAS Project, the Workflow is generic in nature, and could be applied to the design of other repository sub-systems.

5 References

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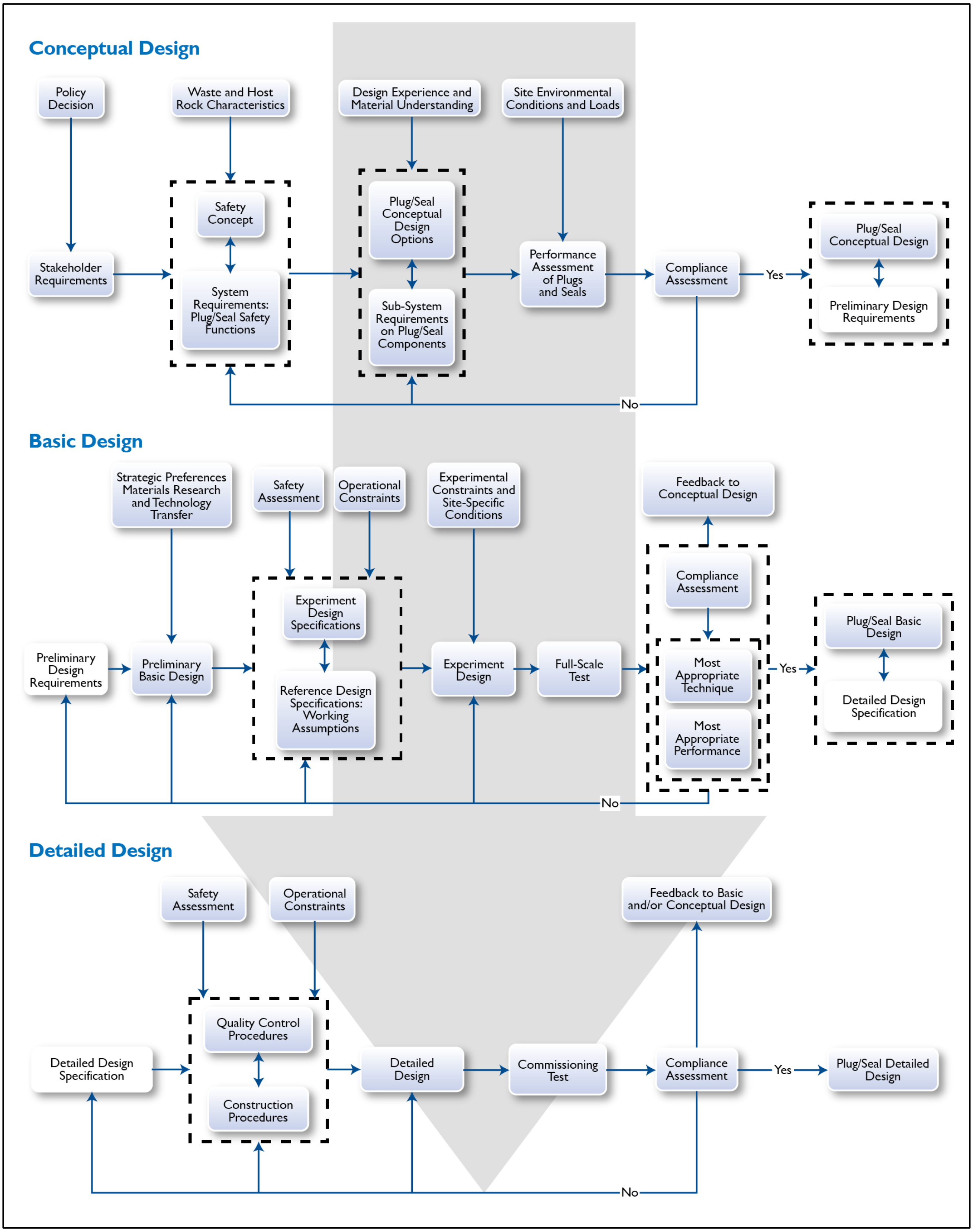

Figure 1: The DOPAS Design Basis Workflow, which illustrates the iterative development of the design basis, undertaken in parallel with the development of conceptual, basic and detailed designs. Dashed boxes are used to show activities undertaken in parallel.

Current Status and Next Five-year Plan of R&D Activities of Mizunami Underground Research Laboratory

Shin-ichro Mikake[1], Teruki Iwatsuki[1], Hiroya Matsui[1] and Eiji Sasao[1]

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The Mizunami Underground Research Laboratory (MIU) project has proceeded in three overlapping phases, “Phase I: Surface-based investigation”, “Phase II: Construction” and “Phase III: Operation”. The construction of research galleries in the MIU has been completed to the GL-500 m depth in 2014. The research activities in Phase III have been conducted in the underground since 2010. Current R&D activities include a gallery closure test on the -500 m level to study recovery processes in the geological environment around a gallery after it has been backfilled and to develop long-term monitoring technology, a post-excavation grouting experiment to demonstrate the feasibility of impermeable grouting technology, and a mass transport experiment. This report introduces the next five-year R&D plan and its current status.

1 Introduction

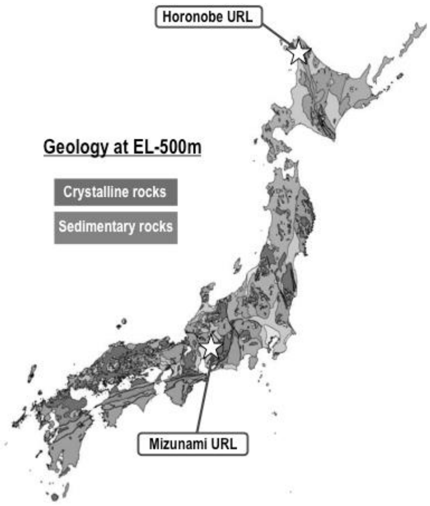

Fig. 1 Predicted geology at EL-500m in JAPAN and location of JAEA’s URLs [2]

One of the features of the geological disposal policy in Japan is the establishment of multiple URLs. The URLs must be distinct from an actual disposal facility, the latter to be selected by the Nuclear Waste Management Organization of Japan (NUMO). URLs in the JAEA projects are classified as purpose-built generic URLs as described in the OECD/NEA report[1)], and are distinct from on-site (site-specific) URLs to be constructed at potential waste disposal sites. JAEA’s URL projects are directed towards improving the reliability of geological disposal technologies and developing advanced safety assessment methodologies. In order to cover the general range of geological environments in Japan, two generic URLs have been built, one is the Mizunami Underground Research Laboratory (MIU) for crystalline rock, and the other is the Horonobe Underground Research Laboratory for sedimentary rock[2)] (Fig.1). The MIU project has proceeded in three overlapping phases, “Phase I: Surface-based investigation”, “Phase II: Construction” and “Phase III: Operation”. The construction of research galleries in the MIU has been completed to -500 m depth in 2014[3)] (Fig.2). Research activities in Phase III have been conducted in the underground since 2010. Current R&D activities include a gallery closure test at the GL-500 m level to study recovery processes in the geological environment around a gallery after it has been backfilled, the development of long-term monitoring technology, a post-excavation grouting experiment to demonstrate the feasibility of impermeable grouting technology and a mass transport experiment.

2 Next five-year plan of R&D activities

JAEA's R&D activities should contribute to establishing the scientific basis for geological disposal in Japan[4] (Fig.3). MIU reached GL-500 m, there was relatively low fractured area in MIU. The next five-year plan of R&D activities will focus on development of the methodologies for detailed site investigations for a repository in Japan. The following points have been considered in defining the future activities:

- Check and review of the second mid-term plan;
- Consider the present progress of geological disposal in Japan;
- Consider the specific features that might affect a geological disposal system in Japan (eg. natural phenomena in an active mobile belt, complex geological structure and deformation of fractures due to location in a tectonic region[5] (Fig.4), large groundwater recharge); and
- Optimization of the project at the MIU.

In keeping with the above policy, three major R&D items[5] were identified as shown in Fig. 5.

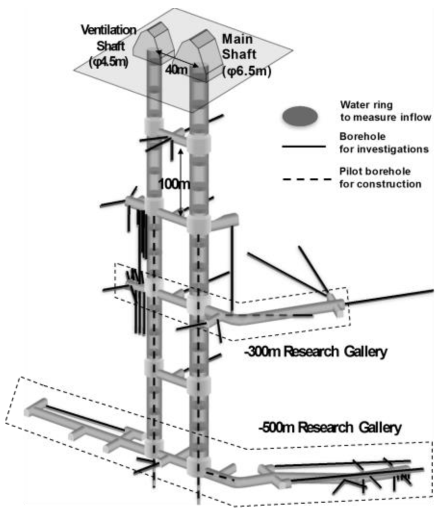

Fig.2 Schematic layout for investigation and drift in MIU [3]

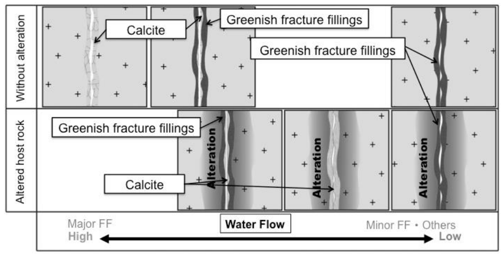

Fig.4 Conceptual model for fractures observed in MIU [5]

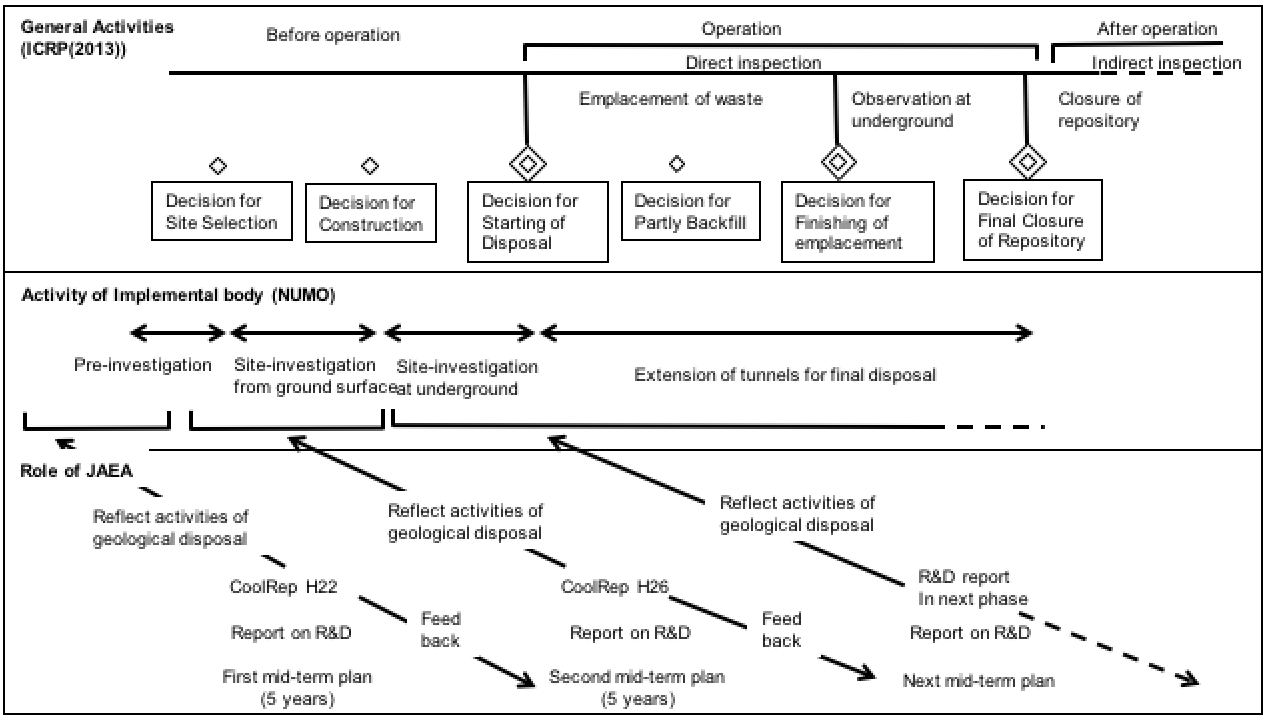

Fig.3 The interrelationship between the progress of geological disposal, and the activities of the implemental body (NUMO) and JAEA R&D activity [4]

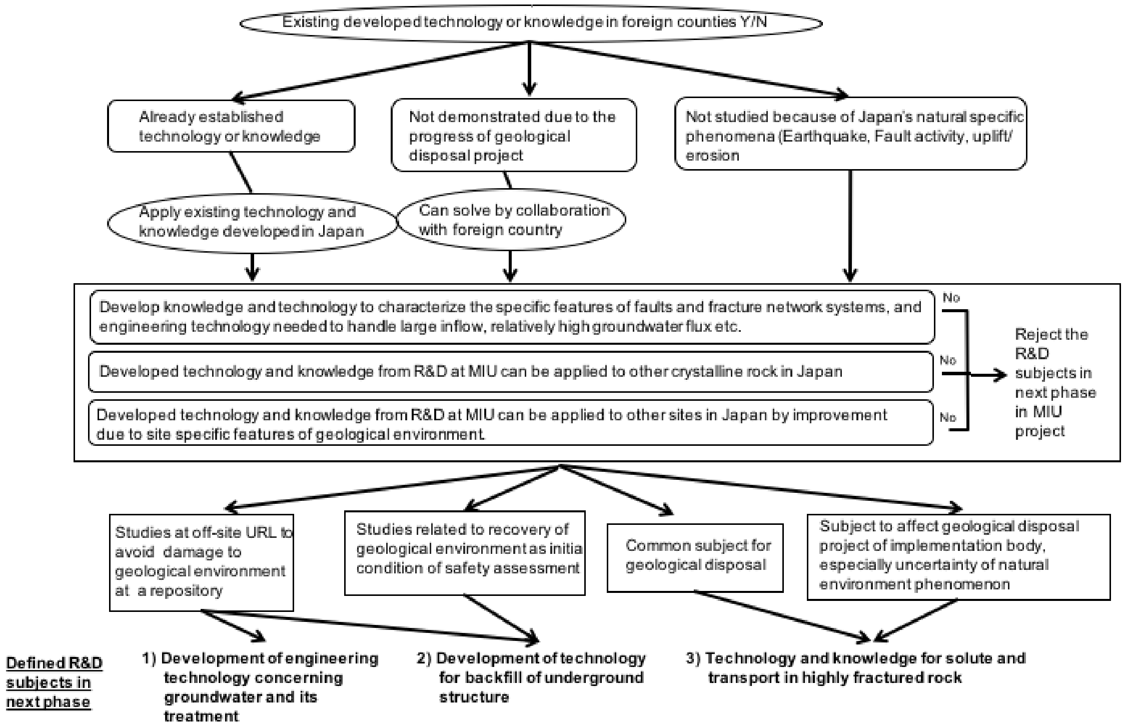

Fig.5 Extraction process of major R&D activities in MIU project in next five-year [5)]

2.1 Development of engineering technologies for preventing of groundwater inflow and its treatment

Generally, countermeasures are applied for construction of underground space because of need to avoid changes to the geological environment near surface, maintain condition of construction work and minimize operational cost for water treatment. In the view of geological disposal, the material used for countermeasures could possibly have a detrimental affect on barrier systems in geological disposal, such as the cement. Moreover, groundwater inflow into a gallery can directly affect the emplacement of buffer material like bentonite.

Therefore, it is essential to develop grouting technology to minimize any influence on the barrier systems.

With respect to these points, the following R&D activities are on-going:

(1) Development of grouting methodology that are a combination of pre- and post-excavation grouting; and
(2) Reasonable water treatment system for deep underground construction in Japan.

2.2 Development of technology for backfill of underground structure

In a geological disposal project, an excavated repository will be backfilled completely to avoid the rapid migration of radionuclides from emplaced high-level waste to the geosphere and to mitigate against human intrusion. On the other hand, safety assessment in postclosure is assumed to rely in part on re-establishment of the baseline conditions of the geological environment prior to repository construction. However, the recovery of geological environment is time dependent related to duration because of low permeable backfill material and coupling phenomenon of T-H-M-C around waste package. Therefore, it is important to develop the technology for backfilling and quantitative evaluation of disturbance of the geological environment in backfilled and of disturbed areas in a repository. The following R&D items are in progress:

(1) Groundwater recovery experiment;
(2) Development for monitoring system after backfilling of underground structures; and
(3) Backfill tests at drift scale.

2.3 Technology and knowledge concerning solute transport in highly fractured rock

Generally, fractures distributed in rock in Japan exhibit a high degree of thermal alteration in a complex fracture network system due to their location in an active tectonic environment and the influence of several major crustal plates. The alteration and sealing of fractures are specific features and processes that will affect the solute transport of radionuclides in crystalline rock. Therefore, it is important to understand their characteristics and long-term evolution by establishment of a site investigation methodology. Therefore, the following tasks have been selected for development:
(1) Development of mass transport models applicable in heterogeneous fracture network systems; and
(2) Development of methodology for quantitative estimation of geological evolution at a site.

3 Current status of MIU project

New five-year plan commenced from FY2015. Here, major topics are introduced as mentioned in previous section.

3.1 Development of grouting methodology - combined pre- and post-excavation grouting

This experiment was done in and around the 500 m Research Gallery south[6]. Pre- excavation grouting was performed to reduce groundwater inflow to below the design construction criterion of 300 L/min as a first step (Fig.6). It was successful with measured inflow of 200-220 L/min in the excavated drift after the pre- excavation grouting.

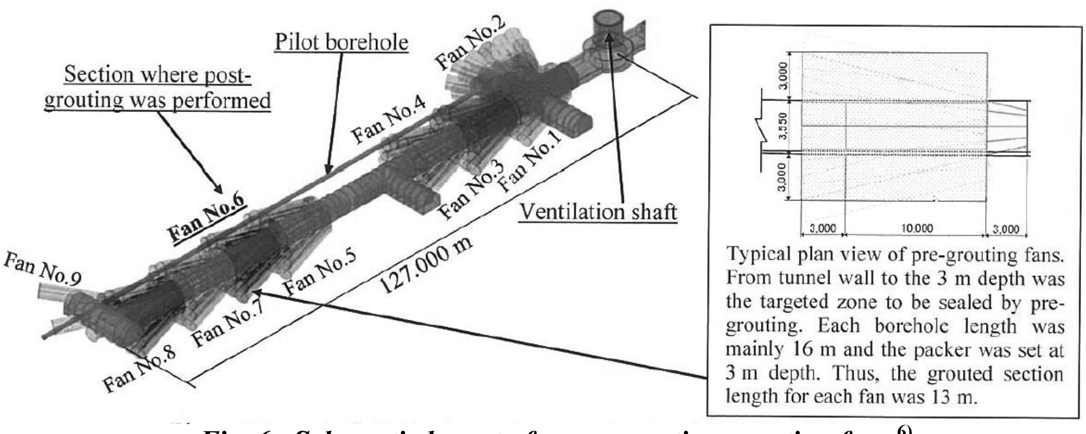

Fig. 6 Schematic layout of pre-excavation grouting fans [6]

Post-excavation grouting work included drilling six circular fan arrays in a 16 m section within the pre-excavation grouting area (Fig.7). Fundamentally, three design comparisons were set: “Material” (liquid-type colloidal silica (CSG) vs super fine cement), “Injection system” (complex dynamic injection vs ordinary static injection) and “Grouting concept” (Sealing outside of the pre-excavation grouting zone vs sealing only the exact grouted zone). The results of the experiment indicated that the application of “CSG”, “Complex dynamic injection” and “Sealing outside of the pre-excavation grouting zone” attained better results than the alternatives. The inflow after post-excavation grouting was reduced by 1/3 this is considered to meet the objectives of sufficiently decreased inflow.

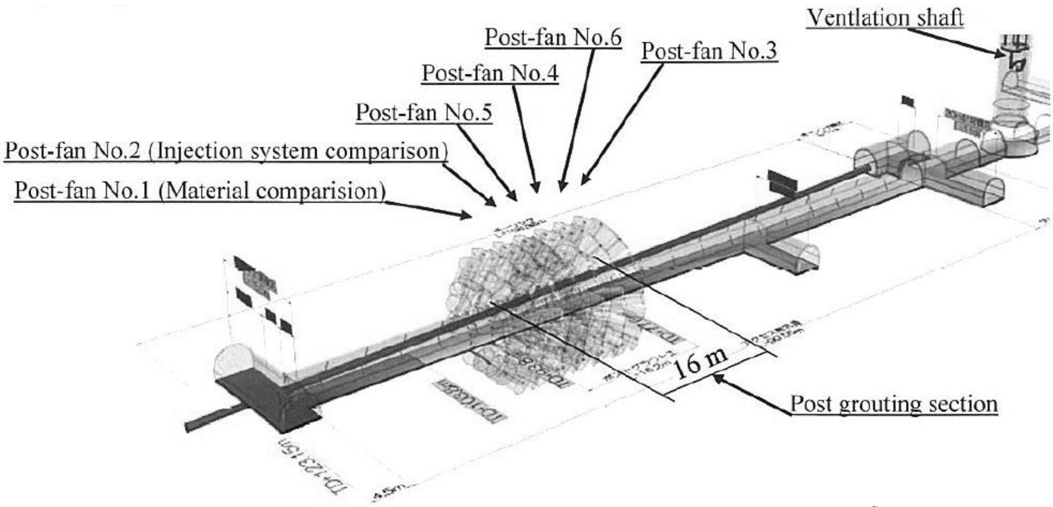

Fig.7 Schematic layout of post-excavation grouting fans [6)]

Then, the post-excavation grouting experiment was performed outside of the pre-excavation grouting zone with designs, applying colloidal silica grouting material and complex dynamic grouting. If pre- and post-excavation grouting were not performed, the groundwater inflow at this experiment section had been predicted to be 1,300 m^3/day. These applied grouting techniques were effective in reducing inflow to 15 m^3/day. These results indicate that the applied post-excavation grouting methodology is effective in reducing inflow and it can be applicable under high groundwater pressure conditions (4 MPa).

3.2 Development of technology for backfill of underground structure

Groundwater recovery experiment mentioned in Section 2.2 is on-going. The experiment focuses on understanding the recovery processes linked to hydraulic pressure and hydrochemistry around underground galleries in fractured crystalline rock.

Fig.8 shows the experimental layout. The impervious plug was constructed before April, 2015 and preliminary testing was done to check the performance of the plug. However, there were defects in the plug due to construction defects and outflow occurred due to seal failure during the preliminary testing. After making the necessary repairs, preliminary testing restarted in January 2016.

The results show that the repaired plug complies with the design concept and meets the specified performance criteria. Water pressure recovery occurred instantly and was at about 75 % that of baseline, in situ water pressure conditions prior to excavation of the 500 m level galleries due to outflow around the plug (Fig.9). Additionally, it was confirmed that alkalization and reduction of isolated groundwater in closed gallery were happening with time.

Henceforth, the water pressure, water chemistry and displacement of rock mass around the drift filled with ground water will be monitored and continue the process to understanding of the recovery phenomenon around the drift.

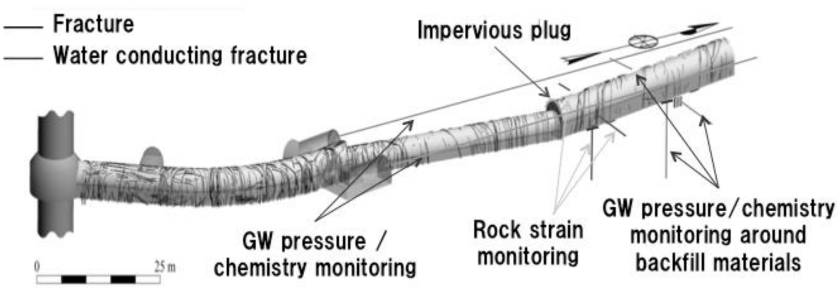

Fig.8 Fracture distribution and monitoring layout at groundwater recovery experiment site [3)]

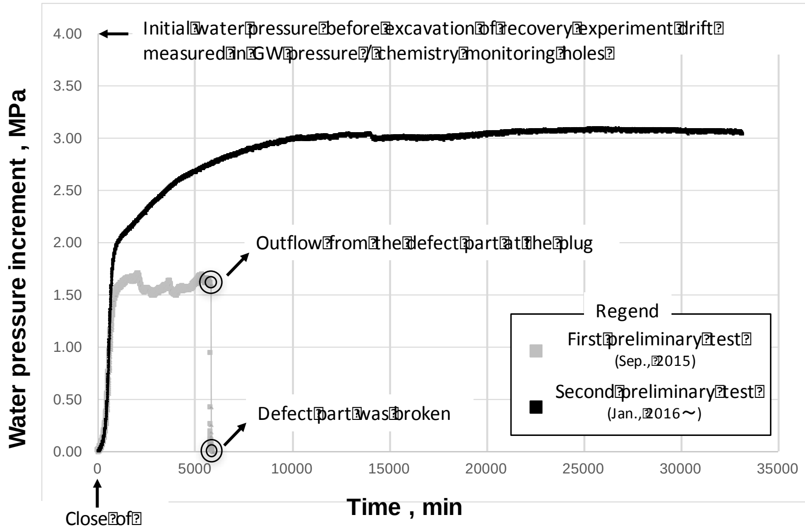

Fig.9 An example of the monitored water pressure recoveries in the groundwater recovery experiment drift during the preliminary tests

3.3 Technology and knowledge for solute transport in highly fractured rock

This R&D activity has been carried out as a collaborative study with CRIEPI funded by METI. In FY2015, several kinds of tracer experiments targeted the specific fractures as in fig.4 were performed at GL-300 m Gallery and several boreholes for the activity were drilled at end of south part of GL-500 m gallery for the investigation. Similar tracer experiments at GL-500 m level are planned for next year.

4 Future schedule of the MIU project

The three main R&D activities (Section 2) will be continued until FY2019 in the project. Also, collaboration with other institutions and organizations will be extended to develop a deeper understanding of the geological environment and for the development of new engineering technologies to enhance confidence in the safety of geological disposal.

5 Acknowledgements

The authors gratefully thank Mr. H. Okumura and Mr. T. Kusano belongs to Contractors (Obayashi-Taisei-Hazama Ando Joint venture and Shimizu-Kajima-Maeda Joint venture) for excavation of research galleries and being worked for impervious plug and grouting.

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Bentonite-based materials for the Full-Scale Emplacement (FE) experiment: design and production steps

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The Full-Scale Emplacement (FE) experiment at the Mont Terri underground rock laboratory (URL) is a full-scale multiple heater test in Opalinus Clay. According to the Swiss disposal concept, it simulates the construction, waste emplacement, backfilling and early post-closure evolution of a spent fuel (SF) / vitrified high-level waste (HLW) repository tunnel as realistically as possible. A granulated bentonite mixture (GBM) and highly compacted bentonite blocks were used to backfill the FE tunnel. The raw bentonite material and the production of the GBM were contracted by public tendering according to World Trade Organization standards (Garitte et al., 2015). Approx. 350 tons of raw bentonite (National ® Standard WP2) were transformed into a GBM. The aim of the GBM production process is to increase the bulk dry density of the raw bentonite material, which is approx. 1.0 g/cm^3, to an emplacement dry density that fits the requirements specific to each repository site. The lower threshold for the target emplacement dry density in the FE experiment was 1.45 g/cm^3 based on correlations observed between the emplacement dry density and other key parameters such as the hydraulic conductivity, the swelling pressure and the thermal conductivity. A minimum dry density of 1.45 g/cm^3 was also found to be a threshold for microbiological activity (Stroes-Gascoyne, 2011). In the FE experiment, the heaters were placed on top of compacted bentonite block pedestals and a 2 m long section of the interjacent sealing section (section foreseen in repository tunnels every tenth canister with steel arch support, according to the Swiss concept) was backfilled with compacted bentonite blocks. The production of 2500 rectangular and 500 curved "top layer" blocks (approx. 70 tons in total) is described in the second section.

1 Granulated bentonite mixture (GBM): design and production steps of a self-compacting material

Blümling & Adams (2008) presented a summary of the work carried out on the use of bentonite pellets as a backfill material as part of the borehole sealing project. The authors showed systematically that the emplacement dry density is dependent on:

- The dry density of individual pellets
- The grain size distribution of the pellets
- The particle shape of the pellets
- The emplacement method

The different issues raised by Blümling & Adams were further investigated in a series of experiments (e.g. Kennedy et al., 2003; Plötze & Weber, 2007).

The design basis for the production of the FE backfill material is discussed based on work by previous authors. Practical lessons from the FE GBM production are then summarised, focusing on:

- The pelletization method and pre-treatment of the raw material required for achieving high quality compaction
- Mixing method for obtaining a broad grain size distribution and hence a self-compacting mixture that will reach a high emplacement density

The production of a bentonite pellet mixture includes several processing steps (Hoffmann et al., 2007). The raw material is generally provided at a gravimetric water content of about 10 – 15 %. It is dried by heating to obtain a lower water content in the range of 3 – 6 %, close to Proctor's optimum and thus associated with higher pellet dry density. The maximum temperature to which the raw bentonite may be exposed during the drying process was determined to be 80 °C. Considering the upper temperature limit, the drying capacity depends exclusively on the grain size distribution of the raw material and the residence time in the heating chamber. With a reasonable production rate of 1.5 tons/hour, the water content of the FE bentonite could be decreased to 4-6%. The aim during the pelletizing process is to increase the pellet dry density, i.e. to reduce the intra-pellet porosity. For the FE experiment, the pellets were produced by compaction between flat rollers (resulting in flat pellets of irregular shape). Although alternative methods exist (see Pietsch, 2005), this method was found to be favourable from an economical point of view with a reasonable production rate (1 to 2 tons per hour). The negative side of this production method was that the desired maximum grain size of about 15 millimetre diameter could not be reached. The bentonite pellets produced were then mixed in a Kniele mixer, providing enough energy input to break some of the pellets and produce a mixture with broad grain size distribution with the aim of reducing the inter-pellet porosity by filling larger pores between large particles with smaller particles at all scales between zero and the maximum grain size. A specific mixing cycle, including high energy mixing of pellets only in the first phase and smooth mixing after addition of 20% of raw material in a second phase, was designed to obtain a grain size distribution close to a Fuller type distribution (illustrated in Figure 1; Fuller & Thompson, 1907). The mixture production rate was approx. 2 tons/hour.

Figure 1: Photo of the granulated bentonite mixture (GBM) produced for the FE experiment.

Intensive testing of the pelletizing and mixing processes resulted in 4 main mixture types. The influence of pellet dry density and grain size distribution are illustrated in Figure 2 where the pouring dry density of the 4 different mixtures is compared. As the mixture density depends on the measurement method, a measurement protocol was designed to compare the mixture dry density during production. Nevertheless, the presented values should not been interpreted in absolute terms. The FE tunnel was filled exclusively with mixture 3 (heated section) and mixture 1 (ISS and section close to plug). The mixture was found to be insensitive to segregation (which would decrease the dry density during horizontal emplacement) as a self-compacting material and to have a large compaction potential.

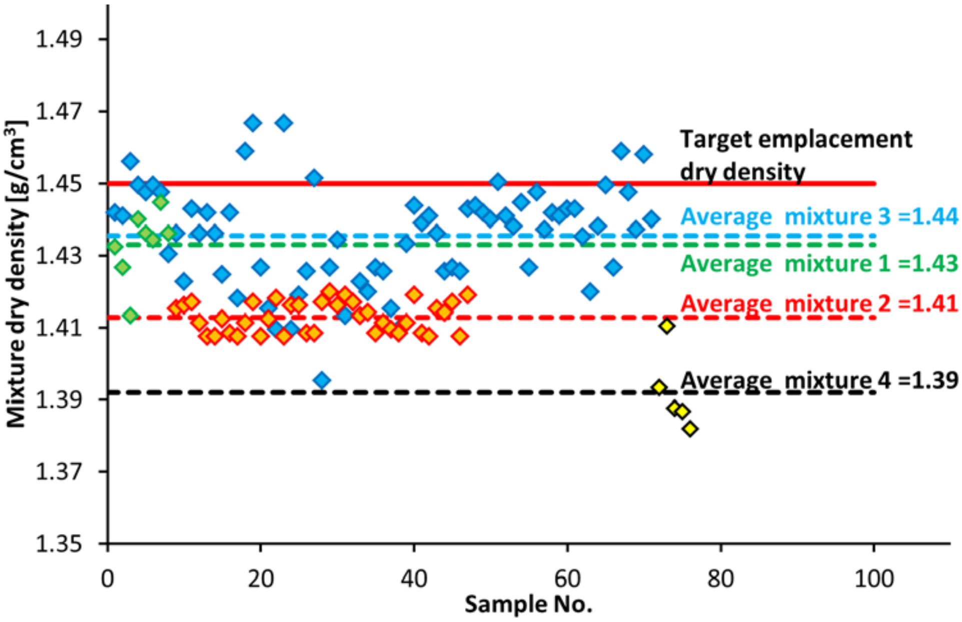

Figure 2: Comparison of the pouring dry density for FE mixture 1 (green dots), 2 (red dots), 3 (blue dots) and 4 (yellow dots), measured every 2 tons during production.
Mixtures 1 and 3 are characterised by a similar grain size distribution and a similar pellet dry density
Mixtures 3 and 4 are characterised by a similar grain size distribution but the pellet dry density of mixture 3 is approx. 10 % higher than that of mixture 4.
Mixtures 1 and 2 are characterised by a similar pellet dry density but mixture 2 is lacking a small amount of fine material and thus deviates from the optimum Fuller curve

Pellets are damaged during the mixing process, which might result in a loss of pellet dry density. This potential loss was estimated by measuring the pellet dry density of different size classes sieved out of the granulated bentonite mixture (Figure 3). Apparently large particles do not suffer degradation, whereas smaller pellets (that were obtained as a result of splitting larger particles) have a pellet dry density loss of approx. 10 %.

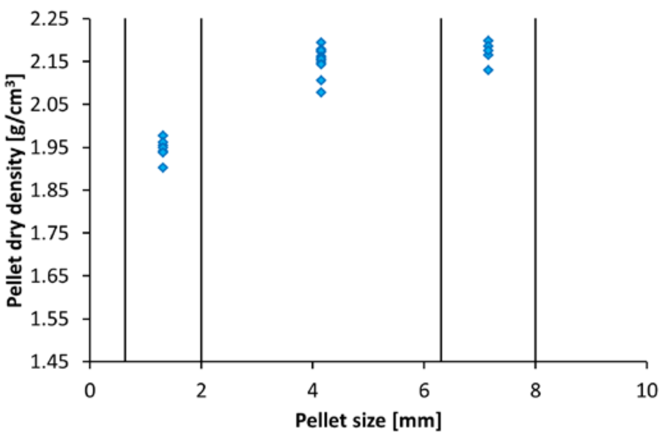

Figure 3: Pellet dry density measured at the ETH using a GeoPyc for three different sizes of pellets (1: between 0.63 mm and 2 mm; 2: between 2 mm and 6.3 mm and 3: between 6.3 mm and 8 mm). 10 measurements for class 1 and 2 and 5 measurements for class 3.

The splitting of the production into four work processes resulted in a satisfactory end-product. A clear and simple recipe (Mixture 3) was identified as producing a GBM at industrial scale that was emplaced in the FE tunnel at an emplacement dry density of approx. 1.5 g/cm^3, with the potential for further compaction. The material is also robust in terms of storage and the many handling steps. The initial requirements had to be slightly modified for practical reasons during production (maximum grain size of the pellets was smaller than desired and the mixture characteristics had to be optimised; final mixture characteristics were within requirements). The procedure was defined on the basis of an extended analysis of existing literature. The main control parameters (water content, pellet dry density, grain size distribution of the mixture) were shown to have a low variation, favouring homogeneous emplacement. The production of a mixture with a Fuller-type distribution is also believed to provide a segregation-resistant material.

2 Compacted bentonite blocks: design and production steps for a highly compacted robust material

For the FE block production, the recommendations made in SKB (2010) summarising the efforts made since the first industrial production (Johannesson, 1999) were followed. According to previous bentonite block productions, the quality and strength of bentonite blocks depends on:

- (i) The compaction method (isotropic/isostatic or oedometric/uniaxial compression)
- (ii) The compaction pressure, pressing time and pressing cycle
- (iii) The initial water content of the raw material
- (iv) The grain size distribution of the raw material
- (v) The type (mineralogy) of the raw material (Na or Ca bentonite)

Two pre-productions were performed to investigate issues related to items ii, iii and v. The sensitivity of compacted bentonite blocks to ambient relative humidity was investigated thoroughly and systematically to optimise the manufacturing parameters (items ii and iii) and to avoid damage to the blocks during in-situ emplacement operations (Garitte et al., 2015).). Four groups of two blocks with different initial conditions were emplaced at the Grimsel Test Site (GTS) and monitored via a dedicated webcam observation system. The experiment was installed on 19.09.13 at 11:00 (RH at that time =70%). The blocks were loaded with a similar pressure to that induced by a heater on the bentonite blocks in the FE experiment.

The test was set up firstly to verify previous laboratory test results and secondly to investigate phenomenologically the mechanisms behind those results. Blocks compacted at a low water content disintegrated very quickly, the support capability was lost within only one month and the first significant fractures appeared in the first days after emplacement (Figure 4). Video cameras placed in front of the blocks and recording a picture every minute allowed the block disintegration behaviour to be monitored. In the low water content blocks, the first fractures appeared within the first hours and the videos (see QR codes in Figure 4) clearly showed the link between fracture development and swelling behaviour. The swelling, caused by water absorption by the relatively dry bentonite from relatively wet air, generated cracks that propagated very quickly because the relatively wet air penetrates into the fractures and expands the fracture inside the block. Drying cracks were also observed in the blocks equilibrated at 35 % air humidity (RH) in the laboratory tests, but these were shrinkage cracks and did not penetrate into the blocks. Blocks produced at a higher water content and thus characterised by a higher equilibrium RH took up almost no water and proved to be very stable over a long time period of approx. 1.5 years.

Figure 4: Resistance of compacted bentonite blocks to exposure time to ambient RH as a function of the production parameters (water content and compaction pressure are indicated at the top of the figure). The QR codes are linked to time-lapse videos of the block evolution.

For the FE bentonite block production, an average block dry density of 1.78 g/cm^3 was achieved. All other requirements, selected according to the state of the art and the pre-tests performed in the FE experiment (geometry variable, strength, density and water content), were checked for each block during production and were found to be fulfilled and very stable over the production (Figure 5).

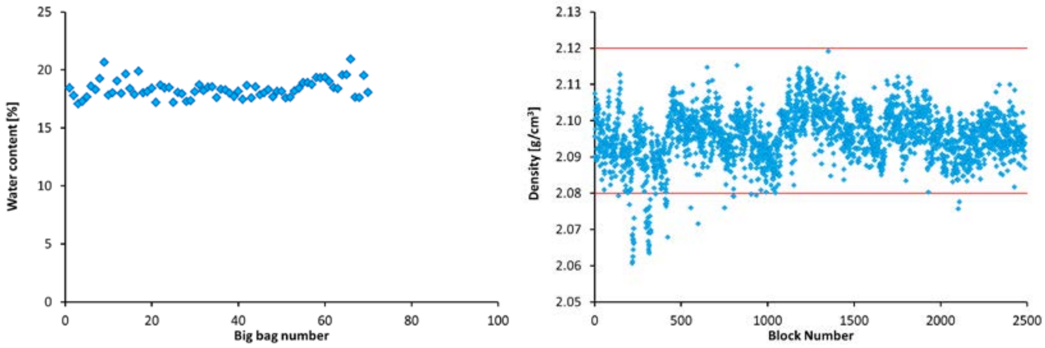

Figure 5: Water content of the raw material after homogeneous wetting (left figure) and block density measured on every block during the production (right figure).

The achieved dry density is a result of the adjustment of the water content of the raw bentonite material and of the compaction pressure to produce bentonite blocks that are as stable as possible with respect to changing climatic conditions in the emplacement tunnel. A higher dry density is possible, but with a loss of resistance to climatic conditions as a consequence. The achieved block dry density value is relatively low when compared to other block productions, but this is believed to be positive as the value comes closer to the emplacement dry density of the GBM. With the equilibrium RH concept in mind and taking extreme care with packaging, the experience acquired in the FE experiment shows that it is possible to store compacted bentonite blocks for a full year (or longer) without affecting them. Nevertheless, it was suggested that it might be impossible to produce blocks with an equilibrium RH higher than 70 %. If the ambient RH at the repository site is higher than 80 %, this might result in practical problems during the emplacement activities, but there are technical possibilities for drying the air in the emplacement tunnel.

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The CIGEO FSS Experiment
Construction of a Seal Industrial Prototype
DOPAS 2016 SEMINAR – Poster Session

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----SUMMARY----

The **Full Scale Seal** (**FSS**) Experiment is one of various experiments implemented by Andra, within the frame of its Deep Geological Repository (aka DGR or Cigéo) Project development, to demonstrate the construction feasibility of the plugs and seals likely to be built, at the time of Cigéo progressive closure operations, in work openings such as shafts, ramps, drifts and/or disposal vaults.

FSS was built inside a reinforced concrete built horizontal drift model (aka "test box") fabricated for the purpose, and located inside a surface hangar in Saint-Dizier (France) to mimic the *in situ* conditions.

The main FSS components concerned by the construction experiment (backfilling) were the 2 low pH concrete monoliths (aka "containment walls") and the swelling clay core (bentonite) between them (cf. Fig.1). A support wall made of low pH concrete blocks was also erected to maintain the swelling clay core during the backfilling of the test box.

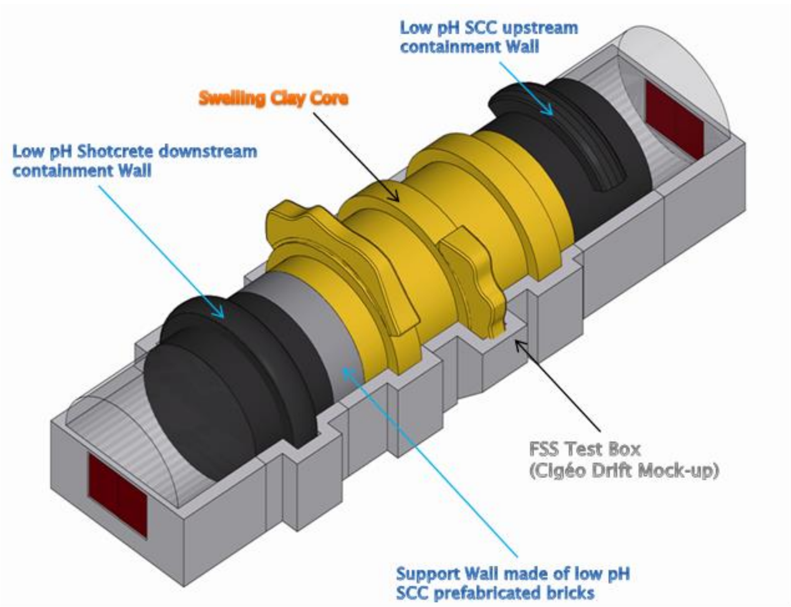

Fig.1: The FSS test components

The development of the materials used in FSS (low pH SCC and shotcrete, bentonitic mix) and their use in the construction process are shown. The construction story and the main experiment outcomes are also briefly summarized in the **FSS Poster**.

1. Introduction

The drift model specifically built for the FSS experiment was 7.60 m ID and 35.5 m long. The drift section made with reinforced concrete was 70 cm thick, incorporating “host formation break outs” (recesses) likely to be generated (i.e. in real Cigéo underground conditions) by the drift lining deposition (Fig.2 shows the test box before backfilling operations). Representative underground ambient conditions (i.e. temperature around 18-30°C & hygrometry level at some 75%) and mine like ventilation were maintained within the drift during the construction period. The low pH 5m long self-compacting concrete (upstream) and shotcrete containment walls (backstream) closed the volume of the swelling clay core (13.5 m long).

Polycarbonate windows were positioned for observation needs and reservations were integrated to the model structure for further monitoring and logging needs. The seal construction was preceded by laboratory work tasks including mainly the formulation and characterization of the materials concerned, in order to check that the measured performances would be in line with the specified requirements. This was true for the clay material constituting the swelling core (most likely bentonite pellets and bentonite powder), the low pH shotcrete and the low pH self-compacting concrete (to make sure that the formulations could fulfil the physical as well as the chemical specifications). Then a campaign of intermediate scale emplacement tests (metric or plurimetric) was run before adopting the final industrial solutions to check whether the fact of working at a larger scale had an impact on the emplaced material characteristics or on the emplacement method *per se*.

The FSS construction experiment being a technological demonstrator, it did not focus on the phenomenological survey (and as a consequence on the performance and behaviour forecast of the bentonitic material emplaced). A specific saturation test at a metric scale (cf. **REM Poster** and **REM Paper**, N. Conil *et al.)* was specifically and separately launched for this purpose.
Dry density measurement methods and tools were implemented, using specific devices (TDR sensors, gamma-gamma logging tool, and also a specific penetrometer) for the bentonite material. To follow the concrete behaviour during hydration, temperature and shrinkage were also monitored, thanks to sensors pre-positioned inside the test box (before backfilling).

The FSS started on mid-2012 and was completed by end of 2014 with a “clever dismantling” of the test box and seal components: it was a “post-mortem” investigation added to the initial construction objectives of FSS. All the work sequences were video-taken and a chronogram of operations established to assess the overall time needed to build a complete seal in Cigéo.

The main milestones were:

i. Studies, formulations & characterization of materials (slow pH SCC and shotcrete): end 2012-mid 2013,

ii. Construction of test box: end 2012-mid 2013,

iii. Construction of seal components (SCC monolith, swelling clay core and shotcrete monolith): mid 2013 – end 2014,

iv. Monitoring and commissioning of seal components: end 2013 – end 2014,

v. Dismantling & additional investigations: mid 2015 - end 2015.

Fig.2: The FSS test box equipped with mine like ventilation before backfilling operations

2. Outcomes of FSS Construction & measurement systems

2.1 Construction issues

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 4 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 minimized 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).

The production of dust during the bentonite mix transfer or backfilling operations needs some additional mitigation (e.g. water mist forming a curtain or/and some tarps around the silos).

2.2 Measurement systems for the low pH 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 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.

2.3 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 temporary conclusions on the monitoring and commissioning tools deployed are as follows:

- Penetrometry is a promising solution but is far from ready for Cigéo application (as calibration is difficult and should be reconsidered for oblique and longitudinal applications). Andra will further explore this technical development in the future.
- Observation windows: visual observation was difficult at times due to dust build-up on the polycarbonate folio. This type of device is not applicable to Cigéo. When observable, it was noticed that effectively, the summital recesses were less properly backfilled (e.g. containing pellets only) than the bottom recesses, qualitatively corroborating the measures provided by gamma-gamma logging or Penetrometry.
- Results obtained from gamma-gamma logging are consistent with measured values made Penetrometry and TDR technology. This device however needs additional development and a better calibration. Besides, logging requires pipes inside the 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 other 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 future full-scale seal tests to be conducted at the beginning of Cigéo during the Industrial Pilot Phase.

REM (Resaturation test at metric scale)

Setup and first results

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[1]Andra CMHM, France

Andra's experiment REM consists in the artificial resaturation of a mixture of pellets and crushed pellets of bentonite (MX-80) at a metric scale. It started around one year ago and evidenced the partial hydration of the lower part of the core which is in contact with water. Blind simulations had predicted a full resaturation time of 30 to 60 years. Very few hydraulic responses have been measured so far but no mechanical responses (i. e. swelling pressure). In parallel tests in laboratory gave information on influence of water used for the hydration and swelling value which will be expected.

1 Background

In the design phase for the CIGEO deep geological disposal project, Andra plans to build drift seals to re-establish site integrity and safety on closure. Various technical solutions have been considered, involving a swelling clay core inserted between two concrete support structures. In order to check the industrial feasibility of this facility, a Full-Scale Seal (FSS) technological demonstrator was produced with the support of the European DOPAS project (Foin et Bosgiraud, 2016). This demonstrator tested industrial equipment by using available and tested technologies to set up and perform a full sealing operation. The seal core was made from a material formed of bentonite pellets and crushed pellets. The core support structures are made of low pH concrete, with cast self-compacting concrete for the front structure and shotcrete for the rear structure. Given the size of the facility, a phenomenological test cannot be envisaged. The saturation of a decametric-sized core would take hundreds of years and would generate very high levels of mechanical stress on the model structure due to bentonite swelling. A series of experiments are therefore being implemented in addition to the FSS demonstrator in order to test the phenomenological aspects and the seal's hydro-mechanical behaviour under real operating conditions. The REM experiment is complementary to the FSS experiment and will demonstrate the feasibility of resaturating the mixture used in FSS and analyse the pellet mixture's behaviour during resaturation at a scale that is difficult to achieve with standard laboratory equipment (decimetric scale at most).
The experiment has two parts: the construction and operation of a metric-scale mock-up, carried out in September 2014, and the performance of in-laboratory hydro-mechanical tests (centimetric and decimetric scale).

2 Scope and objectives

The REM (Metric Scale Resaturation) experiment (Conil et al., 2015) has been designed to study the water saturation of the bentonite mixture of 32 mm pellets and crushed pellets used in FSS. The originality of this mock up is its scale. The cylindrical cell where the bentonite mixture is placed has a one meter height and one meter diameter. FSS and REM experiments are complementary: FSS objective is to demonstrate the construction feasibility of a seal and REM is dedicated to study the behaviour of the bentonite during water saturation phase. To have a better understanding of the bentonite behaviour under several conditions (water composition, dry density) and to characterize its hydro-mechanical properties, in-laboratory tests (centimetric and decimetric scale) has been performed by the CEA/LECBA laboratory (Gatabin et Guillot 2015).

3 Method

In order to get as close as possible to in situ conditions, several criteria were defined for experiment design. To ensure comparable properties (permeability, swelling pressure) between the mock up and FSS demonstrator, equivalent dry density must be similar in both systems. Equivalent dry density primarily depends on the compacting rate, residual void level and initial water content. The reduced dimensions of REM prevent the use of the filling tool used in FSS (use of worm drive to transport materials). For REM, the pellet emplacement was manually, with successively layers of pellets and crushed pellets.

The dimensions of the vessel are primarily related to the initial target swelling pressure of 7 MPa. In a metric-scale object, there is a high load on the walls of 700 tonnes per m^2. In order to facilitate filling and avoid creating "arching" effects that prevent the material from reaching uniform density, sensors had to be spread out with intervals of at least the size of the pellets, and for the experiment as a whole, the vessel diameter had to be at least equal to its height (slenderness ratio of 1 to minimise edge effects). The vessel is cylindrical with a 1 m internal diameter and an inside height of 1 m. The vessel comprises a 40 mm thick confinement cylinder, with 2 lids fitted with sintered stainless steel porous discs in the bottom part and air vents in the top part (Figure 1).
The vessel environment comprises the vessel hydration or injection circuit and the air outflow circuit. The injection system must supply water to the sample's inside surface and regulate and/or quantify the quantity of water provided.
The hydration water is taken from a borehole of the URL. Since April 2012, water has been collected its composition is monitored by sampling and laboratory analysis.
In order to get as close as possible to these very low flow conditions and given the usual flow rates observed in underground laboratory experiments, it had to be possible for the injection rate to be very low, at least for the first weeks/months. At first, the hydration rate was set at 50 ml per day, which was representative of the water supplied from a desaturated rock mass close to a seal. This rate is the flowrate reported at the vessel surface, which was measured in situ in boreholes PAC1002 and POX1201 (Vinsot et al., 2011) at the underground laboratory. Finally, once the pressure has risen, the hydration system will be directly connected to the feed tank for gravitational supply driven by the suction of the sample, a scenario corresponding to a saturated rock mass supplying continuous water in sufficient quantities.

The instruments were provided and installed by CEA (Gatabin and Guillot, 2014). They must precisely measure changes to the sample's hydrological and mechanical state (swelling pressure, pore pressure). These considerations influenced the choice of sensors and their location in the vessel. The sensors must be sufficiently unobtrusive to measure the inside surface as closely as possible and sufficiently robust to function for as long as possible.

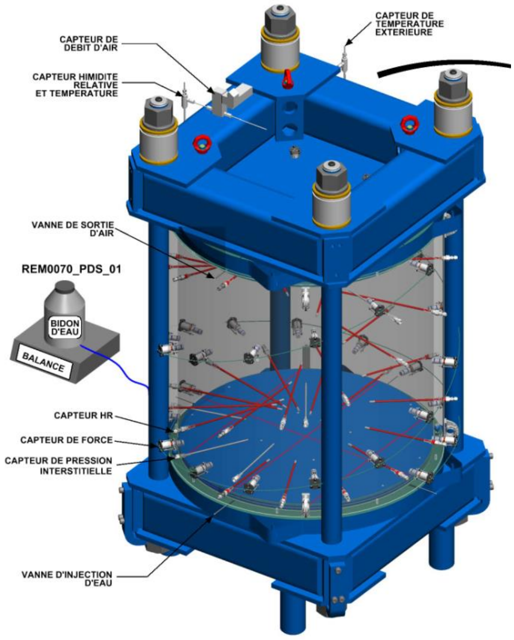


Figure 1 Schematic representation of the REM mock-up

Three types of sensors have been installed on and in the vessel. These sensors provide five different types of measurements: total radial and axial pressure, pore pressure, relative humidity and temperature. Off-the-shelf sensors were adapted by CEA specifically for this configuration. All measurements are transmitted to the outside of the vessel. With the exception of the force washers, all sensors can be easily replaced, tested or changed if required, without modifying test operation.
The radial sensors are distributed at various heights in a spiral around the confinement cylinder, perpendicular to the hydration flow (***Figure 3***). Including sensor in around the vessel to measure the temperature and the humidity in the room, REM experiment includes a total of 109 sensors.

All these measurements will give a three-dimensional view of the hydraulic and mechanical behaviour within the test, throughout the entire resaturation phase. They will also allow to determine when saturation is achieved from a hydraulic (pore pressure) and mechanical standpoint (swelling pressure). Observations in smaller scale tests show that stress balance is always achieved before pore pressure balance.

4 Results

4.1 Metric-scale experiment

The experiment was installed in September 2014. After installing the first layer of sensors (figure), the materials were poured out of buckets weighing around 20 kg, until reaching this 100 mm height, alternating between pellets and crushed pellets in the mass proportions of 70%/30% (Figure 26). The end goal was to achieve final dry density of 1.50 g/cm^3 while guaranteeing uniform filling throughout the volume of the vessel. This method meant that the emplaced density in each layer could be easily assessed in order to make adjustments with the following layer, if required. This operation was repeated by 100 mm layer, alternating with the implementation of humidity sensors and pore pressure sensors. Each bucket of material was precisely weighed.

Figure 2 Installation of the first 100 mm of the pellets / crushed pellets mixture

Hydration was launched immediately after the installation. As previously mentioned, the vessel is currently hydrated from the bottom at a constant flowrate of 50 ml per day using a pump connected to a water tank. The water tank is placed on scales to monitor weight of injected water.
Relative humidity measurements are presented in Figure 4. To facilitate comprehension of the results, measurements are broken down by section as shown on Figure 3.

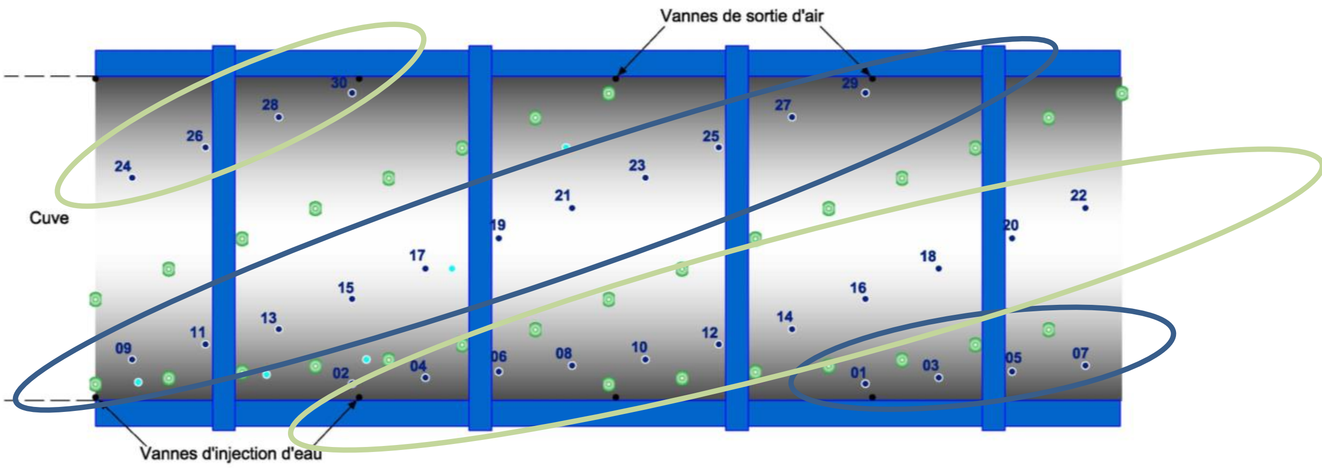
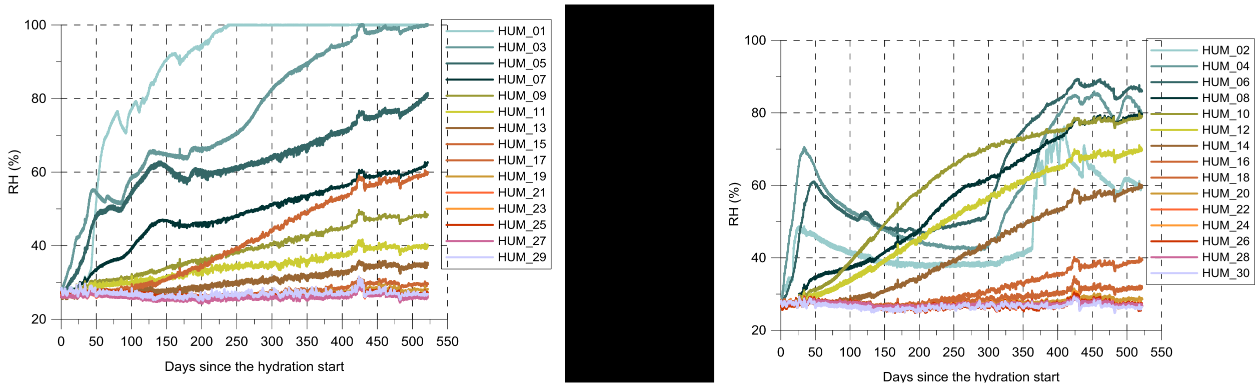


Figure 3 Sensors on the REM experiment vessel - Position of humidity and temperature sensors on the REM vessel – Section 1 in blue – Section 2 in green

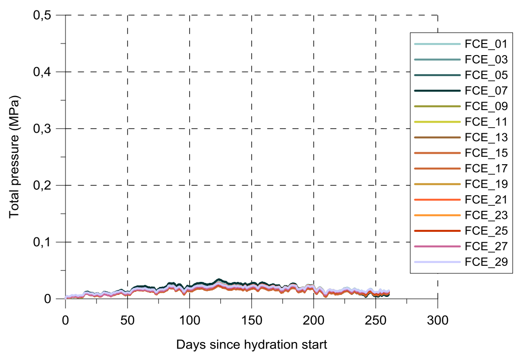


a) section 1 b) section 2

Figure 4 Relative humidity measurements in the REM vessel

On average, RH was at 27% at the start of hydration. The most reactive sensors were sensors close to the injection system. One of them Sensor 01 has even reached 100%. It will be removed and its position resealed in order to avoid backflow and leaks along this sensor. The other sensors that react, both in section 1 and section 2 are also located at bottom of the vessel and close to the point where water enters the sintered metal. Above 300 mm, the sensors react very little or not at all. Analysis of the curves shows that hydration in the vessel is not uniform. If the sensors located at the same depth are compared, the hydration kinetics and also the amplitudes are different due certainly to a small inclination of the cell. No influence of the temperature variation is observed.

The measurements obtained by the load cell around the vessel are presented in Figure 5. As expected, variations are very small or zero showing that there is no swelling pressure. The same tendency is obtained from the sensors installed in the lid. In fact currently, the bentonite is in the volume expansion phase and the macropores are gradually closing. Logically, once all the macrovoids have closed, the load cells should start to react.



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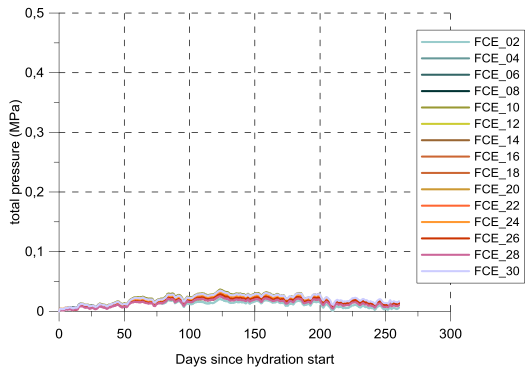

a) section 1 b) section 2

Figure 5 Pressure measurements in the vessel

4.2 Laboratory tests

The chemical characteristics of concrete pore water can significantly disrupt the hydro-mechanical performance of the bentonite mixture after saturation, especially if emplacement takes place at a low saturation level (very dry material like FSS and REM). Due to the direct contact between concrete and bentonite plug in seals (concrete liner or containment plugs); it is therefore important to test this influence on swelling pressure and permeability by using representative samples. All the samples tested have a dry density of approximately 1.50 g/cm^3, similar to the FSS/REM mixtures.

The swelling tests were carried out in 4 types of confinement cells to test the scale effects:

- 57 mm axial hydration cell, with one 32 mm pellet and crushed bentonite;
- 120 mm axial hydration cell, containing approximately twenty 32 mm pellets and crushed bentonite;
- 120 mm radial hydration cell;
- 240 mm axial hydration cell, containing approximately one hundred and twenty 32 mm pellets and crushed bentonite.

4 type of hydration water were used in the tests: site synthetic water, water from borehole, low pH concrete water and standard CEM I concrete water.
As the formulation of the supporting concrete in the drifts is still unknown, the tests were carried out using two types of cement water: water from CEM I-type concrete and water from low pH concrete.
"Low pH" concrete, named after the pH value of the pore solution, is chemically different to "conventional" cement-based concrete as its formulation makes extensive use of mineral additives that significantly modify its physical and chemical properties. The pH of both water were

respectively 10,5 for low pH water and 13,5 for standard CEM I water. An example of results obtained in 57 mm cells is given in Figure 6 (site synthetic water in blue an black, low pH concrete water in brown and standard CEM I concrete water in green and yellow). The results are perfectly coherent and reproducible. The impact of standard concrete water (pH 13.5) on swelling pressure is significant in comparison with low pH concrete water (pH 10.6). This difference was much smaller for the tests in 120 mm cells. However the order is the same in both cases: hydration of the pellet-crushed bentonite mixture with high pH water tends to reduce swelling pressure at saturation.
In the 57 mm cell tests, collapse is only seen in the hydration kinetics for the two tests with concrete water at pH 13.5, while in the 120 mm cells, the curve show a turning point at the same time and for the same swelling pressure for all waters.

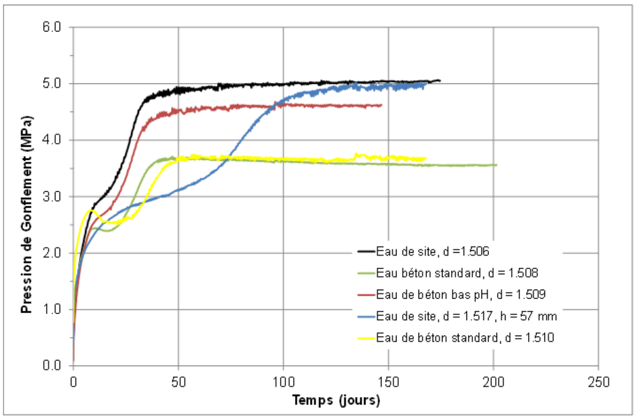

Figure 6 Comparison of swelling kinetics in the 57 mm cell tests according to the hydration water type

Although not all the tests have been completed, it can nonetheless be stated that for all cell sizes tested, the mixture saturates and re-homogenises perfectly.
In terms of water chemistry, the use of high pH concrete water (pH 13.5) significantly reduces swelling pressure. However, low pH concrete water (pH 10.8 used in our tests) has almost no negative influence on swelling pressure. Resaturation with water from the FTP borehole leads to no difference in swelling pressure compared with site synthetic water.
In general no effect of scale was observed and swelling pressure remains of the same order of magnitude. It should be noted that the final dry densities for the FSS in the 240 mm cell were lower than the target value of 1.51, which led de facto to a lower swelling pressure. The failure to achieve this dry density target value is due to the need to create artificial voids in the sample, while keeping it homogenous, in seeking to achieve this density value. The sample surface is therefore uneven, making it very difficult to measure height. This, together with the weight of the piston and various parts of the cell, it is difficult to comply with a given height. Comparison of all the results nonetheless highlights good overall coherence. By extrapolating the swelling pressure for a density of 1.50 g/cm3, LECBA obtains a swelling pressure value of 3.88 MPa.

4.3 Discussion

The measurement realized in the metric test is difficult to discuss at this time because of the very low process of hydration. Preliminary 2D hydraulic simulations performed by Pasteau et al. (2016) gave quite consistent results at the macroscopic scale but local comparison proved to be difficult probably because of the still strong heterogeneity of the mixture at this stage of very early resaturation. They will be very useful to interpret the measurement but a long period of hydration when water front will propagate over several dm.
In contrast the laboratory tests give some first results about the swelling pressure expected from the FFS mixture. In terms of water chemistry, the use of high pH concrete water (pH 13.5) significantly reduces swelling pressure. However, low pH concrete water (pH 10.8 used in our tests)

has almost no negative influence on swelling pressure. This confirms the choice of Andra repository to use low pH concretes in seal zone. Resaturation with water from the FTP borehole leads to no difference in swelling pressure compared with reconstituted water. All the results obtained on laboratory tests highlights good overall consistency. The swelling pressure for the pellets and crushed pellets mixture prepare for FSS and REM with a density of 1.50 g/cm3is about 4 MPa.

5 Conclusions

The REM experiment is complementary to the FSS experiment and should make it possible to study the feasibility of resaturating the mixture used in FSS and analyse the behaviour of a mixture of 32 mm pellets and crushed bentonite during resaturation at a scale that is difficult to achieve with standard laboratory equipment (decimetric scale at most).
The metric scale experiment started in September 2014 and is expected to last several decades for full resaturation of the instrumented metric scale bentonite core. Some relative humidity sensors evidenced a partly hydration of the lower part of the core and no mechanical response was detected so far.
The laboratory test results give an initial idea of the phenomenology and resaturation kinetics affecting the pellet/bentonite mixture for various sample sizes from 57 mm to 240 mm. The mixture resaturates and re-homogenises very well. Different types of water were used to test their influence. No change in swelling pressure was noted with the use of on-site water, compared with reconstituted water. However, the use of high pH concrete water (pH 13.5) significantly reduces swelling pressure. No effect of scale was identified.

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DOPAS EPSP Experiment

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The Experimental Pressure and Sealing Plug (EPSP) experiment being undertaken by Czech Technical University (CTU), SÚRAO and ÚJV a.s. at the Josef underground research centre (URC) and underground laboratory in the Czech Republic as part of the DOPAS project ("Full-Scale **D**emonstration **O**f **P**lugs **A**nd **S**eals"). The project is built around a set of full-scale demonstrations, laboratory experiments, and performance assessment studies and is jointly funded by the Euratom's Seventh Framework Programme and European nuclear waste management organisations. This four year project is running from September 2012 to August 2016, and is being coordinated by Posiva Oy, the nuclear waste management company in Finland.

The EPSP plug has been designed as a prototype plug for a future Czech deep geological repository. It is expected therefore that similar plug will function during the whole of the operational phase of the repository, i.e. 150 years with an expected over-pressure of up to 7MPa. Furthermore, the plug has been designed as a multilayer system consisting of two main structural elements which ensure the overall stability of the system, i.e. concrete blocks and a sealing element - a bentonite section positioned between the concrete blocks. Glass fibre shotcrete with reduced pH was used in the construction of the various elements of the EPSP; the bentonite sealing section was constructed by means of compaction and spray technology.

The plug is tested by means of injecting air/water/a suspension into a pressurizing chamber followed by the monitoring of the performance of the plug.

1 Introduction to EPSP

EPSP is not a specific DGR plug or seal; rather it was built at a similar scale to a disposal tunnel plug and will contribute specifically towards the development of a reference design for such structures. The objective of the EPSP experiment is to test both the materials and technology to be used for implementation, not to test the design and performance of the reference disposal tunnel plug. At this early stage in the Czech geological disposal programme (Pospíšková 2008, SÚRAO 2011), more than 50 years prior to the scheduled commencement of operation, it is considered by those involved 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.

The conceptual design for EPSP experiment includes the following components:

- 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 pressure chamber is sealed with a waterproofing finish.

- Concrete Walls: Concrete walls (made of blocks) were used to facilitate the 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 forms one of the sealing components of EPSP and was constructed using sprayed glass-fibre concrete. The concrete is of relatively low pH.
- Bentonite Pellets: The bentonite pellet zone comprises "Bentonit 75", i.e. a Czech natural and high-smectite content Ca-Mg bentonite. The purpose of the bentonite is to seal and absorb/adsorb any water that leaks across the inner concrete plug. The bentonite zone is 2m long. (more in Vašíček, 2016 and Večerník et. al., 2016)
- 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 designed to hold the other components of EPSP in place. However, should the direction of pressurisation of EPSP be reversed, the outer concrete plug have to perform as well as the inner concrete plug, and, therefore, the requirements are the same as the requirements on the inner concrete plug.

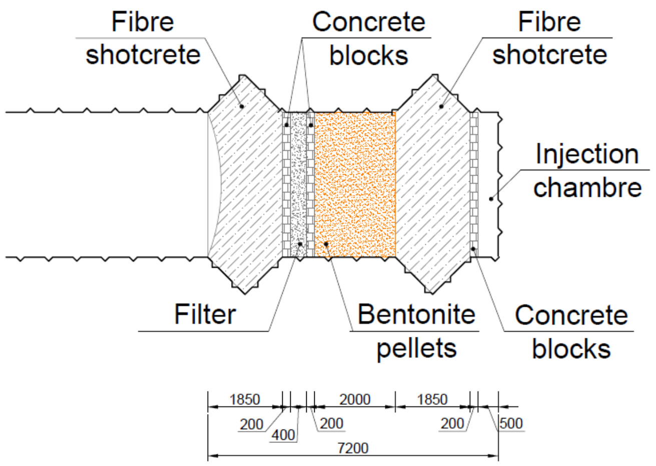

Figure 1 - Scheme of EPSP

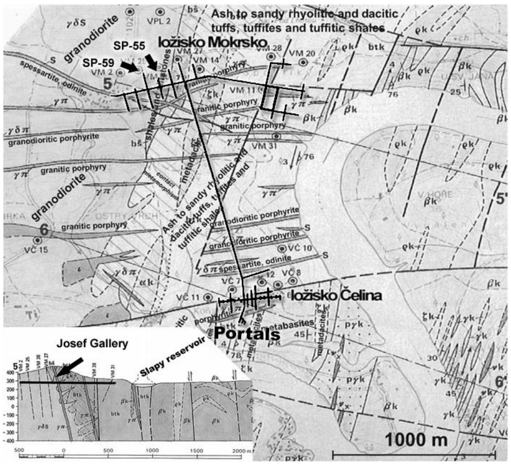

Figure 2 – EPSP location in Josef URL

2 EPSP Location

The EPSP experiment has been built in the Josef Underground Laboratory (Josef URL). Josef URL which opened in June 2007 is a facility of Faculty of Civil Engineering, Czech Technical University in Prague and is operated by the Centre of Experimental Geotechnics (CEG). The Josef URL is employed primarily for the teaching of students from the CTU and other universities. Other activities include research and cooperation on projects commissioned by the public and private sector.

The Josef URL uses Josef gallery which is located Czech Republic 50km south of capital Prague. There is over 8km of galleries and niches of which more than 5km of underground space is currently available and it provides a unique facility for the teaching of students, research connected to a range of projects, training courses, etc.

The EPSP experiment itself is located inside M-SCH-Z/SP-59 experimental gallery niche. The niche was reshaped in advance and surrounding rock has been improved by grouting in order to reduce the water permeability (in order to allow for higher pressures loaded on the plug itself).
The necessary technology for the experiment is located in parallel niche M-SCH-Z/SP-55.
The niches are interconnected by cased boreholes equipped with tubing for pressurization media circulation (4 leading into filter and 4 leading into pressurization chamber) and for monitoring (5 boreholes equipped with sealed cables lead trough).
Experiment construction

3 The experiment construction can be divided in five tasks.

- Task 0 - Niches preparation and documentation
- Task 1 - Rock reshaping & improvement, Instrumented rock bolts, Connecting boreholes, Plugs contact grouting
- Task 2 - Construction works (shotcrete, support structures, filter,…), Technology
- Task 3 - Bentonite sealing
- Task 4 – Monitoring

3.1 Niches preparation and documentation

The niche(s) for the EPSP experiment have been selected in 2012. The selection process was based on results of geological survey of available unground spaces in Josef URC. The detail geological mapping has been subsequently performed once particular niches has been chosen.
In the first part of 2013 the niches have been equipped with networks and prepared for the construction works.

3.2 Rock reshaping and improvement, rock bolts, boreholes

The reshaping and ground improvement activities started in October 2013 with 3D scanning of the existing niche profile. Based on the results of the scanning the precise location of the EPSP experiment was determined.
Once the position of EPSP was fixed, the excavation works started with excavation of the slots in which the shotcrete plugs would be emplaced. The excavation was carried out gradually, at first, rough excavation of rock was undertaken, followed be manual smoothing out.
Selection of the rough excavation method was constrained by a requirement that excavation was undertaken without blasting. This requirement was introduced to minimise the potential for EDZ development. Initially, a hydraulic wedge splitting technique was applied, but this technique was found to be particularly challenging for excavation of the EPSP shotcrete plug slots. Therefore, alternative technique was selected. a second technique was used for construction of part of the outer plug.
The second technique was a pressure disintegration technique using Green Break Technology (GBT) cartridges (non-detonating gas expansion cartridges). The GBT technology significantly accelerated the work on the excavation for the plugs. The excavated opening contour was more precise and smoother, compared to the hydraulic splitter technique.
Following construction of the slots, the rock mass was injected with polyurethane resin at high pressure so as to improve the quality of the host rock.
In parallel to these actions connecting boreholes have been made and later on cased, equipped with cable heads (selected boreholes) and grouted. Thirteen 23 m-long connecting boreholes were drilled between the SP-59 experimental niche and the SP-55 technological niche for the purpose of pressurising the experiment and for instrumentation requirements Eight of the boreholes were used for pressurisation and five for cabling associated with the experiment monitoring system.

The instrumented rock bolts were installed as well. In total 12 instrumented rock bolts has been installed into 3 profiles denoted by the point of origin – originating form niche face, inner slot and outer slot.
These action finished in October 2014.

3.3 Plug erection and technology

The installation of the plug, from installation of the first concrete separation wall to installation of the outer concrete plug, took about 3 months. This does not include the time required for grouting, and monitoring technology. The total time from chamber adjustment to fully operation experiment was 10 months. A major delay was caused by contact grouting of inner plug where several campaigns were done with long waiting time for curing in between. The shotcreting action (plug erection) by itself was very fast. It took less than 24h to erect each plug followed by 1 month curing.

3.3.1 Pressurisation chamber

The walls and floor of the pressurisation chamber were prepared using shotcrete. The thickness of the profiling was such that there was a gap of 100 mm between the remodelled chamber surface and the next structure (the first concrete separation wall). The surface of the remodelled chamber was treated with a 3 mm thin waterproofing finish. The pressurisation chamber was closed by installation of the first concrete separation wall.
The shotcreting of the pressure chamber also served as a test of the technology used for shotcreting of the inner plug.

3.3.2 Inner plug

The inner plug was built using glass-fibre-reinforced low-pH shotcrete. The wet mix shotcreting procedure was used for construction of this plug. The shotcreting was performed in approximately 100 mm thick layers and in a non-stop run in 23 hours. Measurements and observations during the experiment demonstrated that contact grouting between the plug and the rock was necessary to ensure water tightness.
The major influence on the speed of the shotcreting process was logistics. The concrete mix was produced at a concrete plant in Prague and transported by road to the Josef URC and underground laboratory. At the entrance to the facility, the mixture was reloaded into small trucks (each capable of transferring $1m^3$ of concrete), because the small profile of the Josef tunnels limited the size of the trucks that could access the experiment location and therefore limiting the supply.

3.3.3 Filter

The gap between the second and third separation walls was used for the gravel filter. The filter was manually emplaced in steps. At first, the lower part of the walls (approximately one-third to half of the overall height) was erected and the gravel filter was emplaced in the resulting gap. Following this, the bentonite emplacement commenced. Once the bentonite level reached the level of the walls (and the filter) new layer(s) of concrete blocks were constructed and the filter emplaced. The final layer of the separation walls and the gravel was emplaced immediately after shotclaying was completed.

3.3.4 Outer plug

The outer concrete plug was constructed in exactly the same manner as inner plug. The only difference between the inner and outer plug was the installation of grouting tubes around the circumference of the outer plug prior to shotcreting.
Once the plug had cured, grouting was undertaken using the preinstalled tubes. Initial pressure testing of EPSP demonstrated that this grouting was not sufficient and additional grouting was employed in similar way as for inner plug.

3.4 Bentonite sealing

Czech raw Bentonite 75 in powder form was selected as the material to be employed for compaction into pellet form (the powder material was marked as B75 2013). The bentonite B75 was used in form of pellets. Two types of pellets were used. First type (compacted by roller trough die) were used for lower parts. Second type (compacted by rollers, subsequently crashed and sieved) were used for shot clay technology in the upper parts of experiment. More on bentonite selection and pellets manufacturing in Večerník et. Al., 2016 and Vašíček et al.,2016.
Following the results of pilot test (Vašíček et al., 2016) a vibration desk type machines were selected for bulk works. The bentonite was emplaced in horizontal layers with maximal height 3cm which were subsequently vibration compacted. Sprayed clay technology was used for the backfilling of the upper part of the drift. Approx. 5% (1.5m^3) were backfilled using this technology. The construction of the EPSP bentonite pellet layer were done in 9 days between 5th June and 15th June 2015. The total amount of emplaced material is 39.9 tons which were placed into volume of 23.7m3.
Based on project requirements of minimum swelling pressure of 2MPa and maximum hydraulic conductivity of 10^{-12}ms^{-1} of the bentonite sealing a minimum dry density of 1.4Mgm^{-3} was required after bentonite deposition. Two methods of density verification were employed – sampling and total mass balance. Both method shows dry density more than the required level.

3.5 Monitoring

The primary aim of monitoring of EPSP is to investigate the various processes underway inside each plug component, to verify component behaviour and to assist in assessing their performance in order to build a knowledge base for the construction of a future repository plug.
The key processes and locations inside EPSP have been identified and sensors have been specially selected in order to capture them. Monitoring of EPSP focuses on water movement inside the experiment and the experiment’s response to pressurisation.
Water movement inside the experiment is monitored in terms of water inflow, water content distribution within the bentonite seal and water (pore) pressure distribution.
The mechanical response of the plug is monitored by means of strain gauges installed at key locations in the concrete plugs and instrumented rock bolts positioned within the rock. Moreover, contact stress measurement is deployed between the rock and the plug.
Temperature distribution is monitored since it is important not only to understand the hydration heat generated through curing, but it is also used as a reference base for sensor compensation during the loading of the experiment.
An integral element of the monitoring process consisted of the presentation of the measured data for further analysis; therefore the data were instantly available online to end-users via a simple web interface.
The sensor preparation has been carried out in the workshop of the Josef URC facility. Sensor were assembled and equipped with protective tubing from stainless steel. Complete assemblies were step by step transported into the underground following the process of plug erection. In the underground

the sensors have been installed to their final positions or temporary stored on niche side until their location was ready (and then installed).

4 Pressurisation of EPSP

Experimental testing of EPSP started during construction process. The inner plug has been using water and air injection up to 0.5MPa to check water tightness level in order to determine if grouting is need.

Once the outer plug has been cured the main experimental program started with series of short water injection test followed by long term tests at various pressure levels (starting at 0.1MPa going gradually to up to 1MPa). At 1MPa a possible channelling has been detected.

In order to avoid erosion of the bentonite sealing the testing sequence has been interrupted and the sealing section has been artificially saturated from both filter and pressurisation chamber to allow swelling pressure build up (the swelling pressure was significantly lower than testing pressure at channelling event).

The saturation has been later on followed by short pressure test and by injection of bentonite slurry into pressurisation chamber (up to 2.5MPa). The pressurisation chamber was then cleaned up and water injection test resumed.

5 Conclusions

The aim of the EPSP experiment is to develop and demonstrate the feasibility of plug for DGR of radioactive waste in real conditions.

In order to achieve this not only EPSP plug is constructed but extensive monitoring programme is carried out too. The data coming from the experiment and knowledge obtained from both the in-situ and laboratory experiments will be evaluated using numerical analysis techniques and modelling. The final output will consist of the verification of the operational safety of the various structural elements of plugs to be used in DGRs and detailed recommendations for the future design of DGR.

6 Acknowledgement

The research leading to these results has received funding from the European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013 under grant agreement no 323273, the DOPAS project, and form Czech Ministry of education, youth and sports under grant agreement no 7G13002.

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Physical interaction model and EPSP materials characterisation

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Summary
As the EPSP ("Experimental Pressure and Sealing Plug") experiment will not been dismantled during the course of the DOPAS project ("Full-Scale Demonstration Of Plugs And Seals"), the construction of the laboratory scale model was proposed to simulate and describe saturation and interaction processes which can occur in the EPSP plug. Physical Interaction Model (PIM) was focused on changes in physical and chemical properties during the interaction of bentonite, concrete and synthetic granitic water, the identical materials as those used in EPSP construction. Studies and analyses were mainly focused on characterisation and evaluation of concrete leachate pH, material saturation, porosity determination, mineralogy, bentonite cation exchange capacity (CEC), bentonite specific surface area (SSA), water chemical composition after the interaction with concrete and bentonite. The results show that interaction processes occur to some extent, on the other hand duration of the interaction experiment was not sufficient to observe and confirm anticipated changes (e.g. in mineralogy, physical properties etc.). Details of laboratory testing are reported in Deliverable D3.21 (Vašíček et al. 2016).

1. Introduction background

The Czech deep geological repository concept assumes that waste packages containing spent nuclear fuel assemblies will be enclosed in steel-based canisters placed in vertical or horizontal boreholes at a depth of ~ 500m below the surface. Several types of sealing plugs will be required in the repository. The function of which will be to provide for the sealing and closure of individual waste packages not only throughout the period of repository operation, but also following the permanent closure of the facility. Such plugs will have to provide a high level of resistance to the considerable pressure which will be exerted by hydrostatic forces and volumetric changes within the engineered barriers (Dvořáková et al., 2014).
The Czech contribution to the DOPAS project (Demonstration of Plugs and Seals) was focused namely on the EPSP experiment, being built in Underground Laboratory Josef (Svoboda et al., 2016). The objectives of the EPSP experiment were following: to develop, monitor and verify the functionality of constructed experimental plug to determine and describe in detail the materials which are used for experimental plug construction. Shotcrete with low-pH leachate and bentonite pellets were selected for EPSP construction. The local Czech materials were used, including local bentonite B75_2013 (based on bentonite Rokle) and low-pH concrete based on local recipe. According to the plan, all materials used for plug construction have to be characterised prior, during and after the experiments. However, the EPSP experiment will not be dismantled during the course of the DOPAS project, the construction of the laboratory scale models was proposed.

2. Scope and objectives

Laboratory test were focused mainly on two materials, low-pH concrete and bentonite. The main goal was to determine processes ongoing on the bentonite-concrete interface.
Studies and analyses were mainly focused on characterisation and evaluation their physical and chemical properties and also on the interaction with synthetic granitic water (SGW). Concerning concrete, following tests were performed: leachate pH measurement, porosity determination, hydraulic conductivity measurement. Concerning bentonite material, following tests were performed: porosity determination, water content determination, hydraulic conductivity measurement, cation exchange capacity (CEC) determination, specific surface area (SSA) determination and mineral composition analyses. Concerning water phase, the composition and physical and chemical properties were tested.

3. Materials and laboratory tests

Physical interaction model (PIM)

Physical interaction model (PIM) was designed and started in 2014. The schematic geometry of PIM is shown in Figure . The identical materials as those in the EPSP experimental plug were used. Synthetic granitic water (SGW; Havlová et al., 2010) was used as a liquid phase for saturation and interaction processes in the interaction model. PIM consisted of three stainless steel cylinders with a diameter of 8cm and a length of 5cm each. The total length of the model is 15 cm. Such an arrangement reflexes the real in-situ EPSP plug geometry in the best way. Into the middle part of model, bentonite powder was pressed to reach the dry density 1400 kg/m^3. The central bentonite part was surrounded by two blocks of low-pH concrete. One side of PIM was connected to the source of synthetic granitic water, infiltrating under pressure 2MPa. By the end of 2015 year, the PIM was dismantled and material analyses (chemical composition, mineralogy, physical properties, etc.) were performed in order to compare the physical and chemical properties of the materials prior to and following to the termination of the experiment.

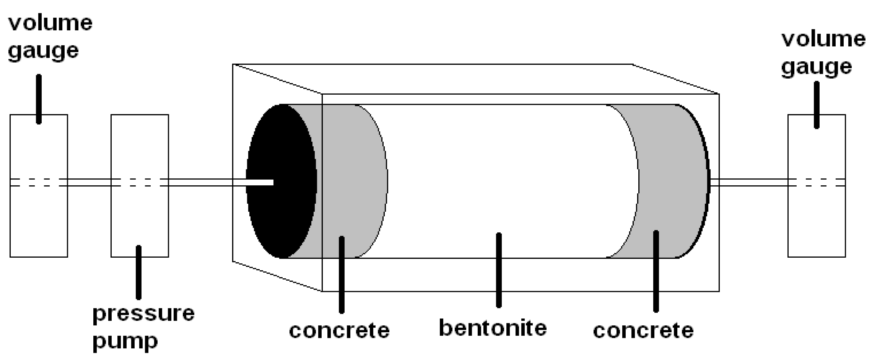

Figure 3-1: The geometry of the physical interaction model (PIM)

Concrete

Low pH concrete was developed under cooperation of ÚJV and subcontractor, however, precise recipe is the internal know-how of the subcontractor. One of required limits was to reach the pH of leachate < 11.7, in optimal case ≤ 11.5, pH measurements methodology followed the one described in SKB report R-12-02 (Alonso et al., 2012). Porosity measurements on both concrete samples from dismantled PIM and on the unaffected concrete samples were performed by water submersion method (Melnyk and Skeet, 1986).

Bentonite

A Czech Ca-Mg industrially milled and sifted non-activated bentonite, laboratory labelled as B75, produced by Keramost, Plc., was used in purposes of DOPAS project (B75_2013). The laboratory tests were performed with two forms of bentonite material (powder, pellets) in order to verify their properties. Prior to the experiments, bentonite material was compacted up to 1400kg/m^3 unless otherwise stated. This compaction value represents the (lower) dry density limit of the material which it is supposed to be able to be achieved by both spray technology and by the compaction of the bentonite pellets and powder for the in situ plug construction. Hydraulic conductivity tests were conducted in two types of experimental cells: small cell (diameter 3cm, length 1.5cm) and large cell (diameter 8cm, length 5cm). After the sample saturation or after performed conductivity tests, the water content and porosity were evaluated.

After PIM dismantling bentonite was sampled from points where some changes were visible (especially if the color (gray and white) spots appeared) compared to solid mass of bentonite block. Mineralogical XRD (X-ray diffraction) analysis on these samples was performed. During the dismantling of the model, the bentonite block was divided into 6 different slices. Each slice was then divided into five parts for the water content analysis. Furthermore, samples of bentonite were taken also from selected slices and those were analyzed for their cation exchange capacity (CEC), exchangeable cations and for their specific surface area (SSA) using EGME method (Carter et al., 1986).

4. Results and discussion

Used concrete material fulfils all required parameters, namely the limit for the leachate pH, having been determined as varying between 11.4 and 11.5 for both concrete parts of EPSP. Leachate pH value was not affected by interaction with bentonite and SGW in laboratory PIM model. In all cases the porosity of concrete evaluated by water submersion method ranged around 20-25% value. The permeability value in the concrete reached $7.9 \cdot 10^{-11}$m/s value with an uncertainty range of 2.7%. In addition, a material dry density value of 2046kg/m^3 was determined for the tested sample.

The processing technology has been identified as the main factor affecting the properties of B75 produced in recent years. Furthermore, it was found that partial activation and/or contamination caused by the presence of an activation reagent affect the composition of the water suspension or water leachate, cation exchange capacity and bentonite pore water composition.

Concerning property determination, the quantity of water flow through the sample was recorded throughout the duration of the experiment (**Figure 4-1**) and coefficients of hydraulic conductivity were calculated from the linear parts of the curves. The values of hydraulic coefficients varies in range $3.1\text{-}5.7 \cdot 10^{-13}$m/s.

For PIM saturation the SGW was taken from the reservoir and pumped to the PIM under the constant pressure 2 MPa using gas-hydraulic pump (as shown in Figure 3-1). First sample collected at the output of PIM was taken longer than 4 months after the start of the PIM experiment. Until this time only saturation of model components was observed. The outflowing PIM water was significantly enriched in all analyzed ions with exception of nitrates and fluorides (see Table 4-1) in comparison with original SGW. Dismantling of PIM it was found that water content in bentonite part slightly decrease (from 40.4 to 35.9 wt%) in the direction of water flow. Bentonite material does not reach the full saturation along the whole mass of bentonite sealing part. Example of bentonite slice distribution from the PIM dismantling, altogether with detemined water content is shown in Figure 4-3. As EGME method provides the value of total specific surface area for expanding clay minerals (sum of external and internal surface), it can point to mineralogical changes in these minerals caused by the alteration processes that results in changes of expandability. As can be seen from

Table Table 4-2**Fel! Hittar inte referenskälla.**, although some minor difference in specific surface area among PIM bentonite samples, generally their values of SSA (specific surface area) are close to the value of the original bentonite B75 pellet. The same situation is observed in case of CEC (cation exchange capacity) of all selected samples. It is clear that the property practical unchanged in comparison with B75 pellet sample, with respect to the analytical determination uncertainties (Table 4-3).

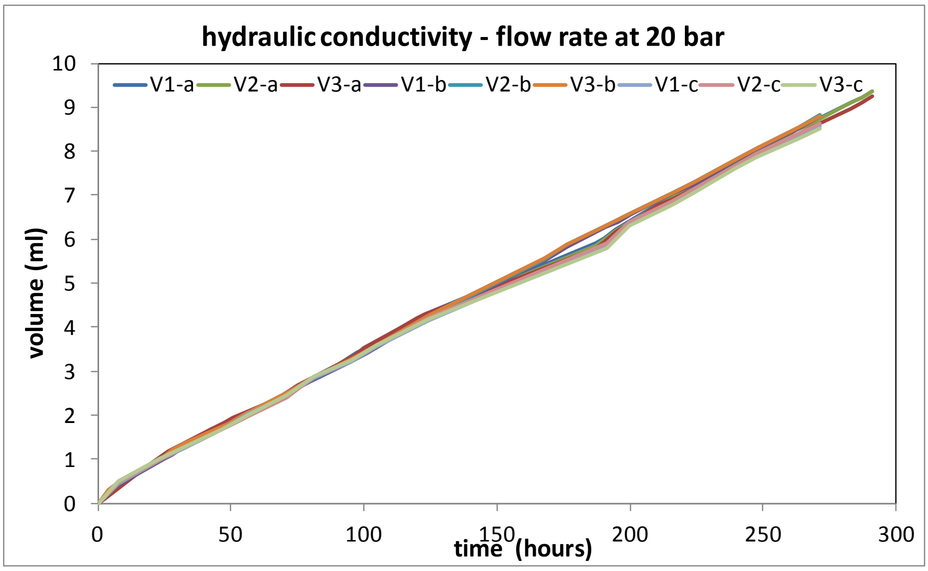

Figure 4-1: Hydraulic conductivity tests on B75 pellets in large cells, the water flow rates

Table 4-1: Comparison of SGW to PIM water composition (N.A. means not analyzed)

	SGW (mg/l)	**PIM water (1st sample) (mg/l)**
Na	10.6	1649
K	1.8	268
Mg	6.4	151
Ca	27.0	1695
Cl	42.4	426
SO_4	27.7	1845
NO_3	6.3	0.1
F	0.2	< 0.1
HCO_3	30.4	N.A.

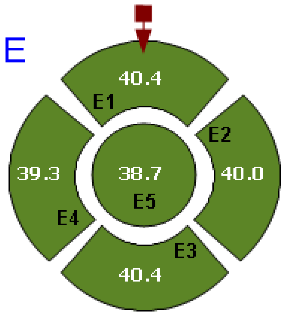

Figure 4-3: Example of a bentonite slice divided to parts for water content determination, with determined water content values (wt%)

Table 4-2: Specific surface of selected PIM bentonite samples

Sample	specific surface area (m^2/g)
2mm	430 ± 28
5A	491 ± 17
5C	476 ± 18
1E 2E 3E 4E 5E	482 ± 36 466 ± 7 465 ± 7 478 ± 11 491 ± 8
B75 pellet	453 ± 18

Table 4-3: CEC of selected PIM bentonite samples and B75 pellet

Sample	CEC (meq/100g)
2mm	55.1
5A	56.6
5C	57.3
1E 2E 3E 4E 5E	57.0 54.9 55.6 56.9 58.0
B75 pellet	56.4

Details of laboratory testing, results and discussion are reported in Deliverable D3.21 (Vašíček et al. 2016).

5. Conclusions

LPC concrete mixture was developed an applied in EPSP construction. The tests confirmed that this material fulfil all requirements stated at the beginning of the project. No changes in

the concrete leachate pH, porosity and mineralogy prior and after the interaction with bentonite and synthetic granitic water in physical interaction model were observed.
The properties of bentonite materials were studied in order to confirm the selection of the most suitable material. The analysis of chemical composition and mineralogy, the measurement of pH in bentonite suspensions and distilled water with different ratios, the analysis of leachates and the measurement of porosity were conducted with regard to B75_2013 bentonite which was selected as the construction material for the EPSP. Further, it was confirmed that the main properties of B75-2013 bentonite fulfil all the expectations, limits and requirements for the EPSP sealing part. It was observed no significant changes in mineralogical composition or presence of newly formed phases after the dismantling of physical interaction model. It is evident, that interaction processes between concrete and bentonite in performed physical interaction model did not reach to significant rate that can influence their properties, contributing to the material safety properties.

6. Acknowledgement

The research leading to these results has received funding from the European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013 under grant agreement no. 323273, the DOPAS project.

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The laboratory models for EPSP experiment in DOPAS project - the saturation of bentonite pellets and bentonite powder

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Summary
As the EPSP underground laboratory experiment would have not been dismantled during the course of the project, the construction of physical hydraulic models (PHM) at the laboratory scale was proposed in the laboratory work plan. The aim of physical hydraulic models was to describe the hydraulic and mechanical processes during saturation of bentonite and give sufficient data for subsequent numerical modeling. Two physical hydraulic models were therefore constructed. The first one use bentonite powder and the other one use bentonite pellets, both materials being used during EPSP construction. Bentonite with bulk density of 1 400 kg/m^3 was pressed into the stainless steel chambers, equipped with a number of sensors and gradually saturated with water under 2MPa pressure, simulating presumed plug performance. The experiment was then dismantled after defined time period. Bentonite material was divided into the layers with an estimated thickness of 1cm. The water content in each layer was then determined.

1. Introduction background

The Czech deep geological repository (DGR) concept assumes that waste packages containing spent nuclear fuel (SNF) assemblies will be enclosed in steel-based canisters placed in vertical or horizontal boreholes at a depth of ~ 500m below the surface. The void between the canisters and the host crystalline rock will be filled with compacted bentonite which will make up the final engineered barrier. DGR safety will be enhanced by the efficient performance of the plugs and sealing systems which will make up an important part of the overall disposal system.
One of the experimental plugs within DOPAS project was built at Underground Laboratory Josef (EPSP) - see Svoboda et al. (2016).
As the EPSP underground plug will not be dismantled during the course of the DOPAS project, the construction of physical hydraulic models (PHM) at the laboratory scale was proposed as an efficient method to verify model presumptions and gain data for further modeling.

2. Scope and objectives

The aim of physical hydraulic models was to describe the hydraulic and mechanical processes during bentonite saturation and to provide data for subsequent numerical modeling.

3. Laboratory tests

3.1 Physical models

Two physical hydraulic models (PHM) were constructed, both being based on nine stainless steel chambers of cylindrical shape with approximate dimensions 0.05m in length and 0.08m in diameter (total length of bentonite in PHM is 45 cm, Fig. 1). Bentonite with bulk density of from 1 400 kg/m3 (the same bulk density as in the EPSP experiment, material is described in detail in report Vašíček et al., 2016) was pressed into the nine chambers and was gradually saturated with water under pressure. The level of water pressure was based on the field testing of the grouted rock at the Josef Underground Laboratory, being set on 2MPa. After defined time period the bentonite material was dismantled and divided into layers with an estimated thickness of 1cm. The water content in each layer was then determined. These data were combined with measured data of relative humidity and all together were compared with the retention curve derived by blocks method on small samples.

The following data were determined during the experiments:

- The volume of water infiltrated into sample
- Pressure, under which water has been pressed into the sample
- Development of relative humidity (RH) in observation points
- Development of swelling pressure at the end of the sample

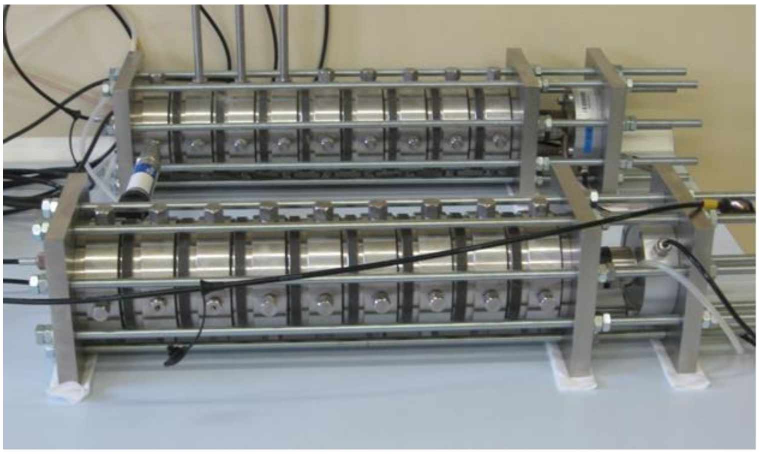

Fig. 1 Two physical hydraulic models, one filled by bentonite powder, second one filled by bentonite pellets.

3.2 Results and discussion

The PHM results with bentonite powder are shown in Fig. 2 to Fig. 4. Observing the Fig. 2 to Fig. 4 it is clear that the material saturation rate decreases in the flow direction. Furthermore, it is apparent that the response of swelling pressure is consistent with the response of the relative humidity at a distance of 2.5 cm from the sensor for measuring the swelling pressure (the distance between these two sensors is 2.5 cm).

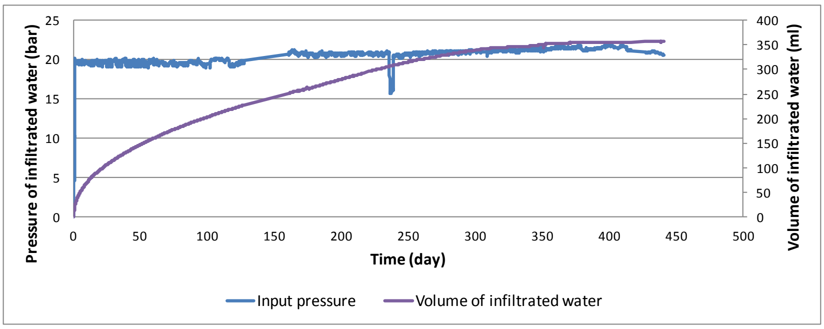

Fig. 2 The pressure and volume of water infiltrated into the sample. Pressure drop around 230 days was caused by the failure of the pressure reducing valve.

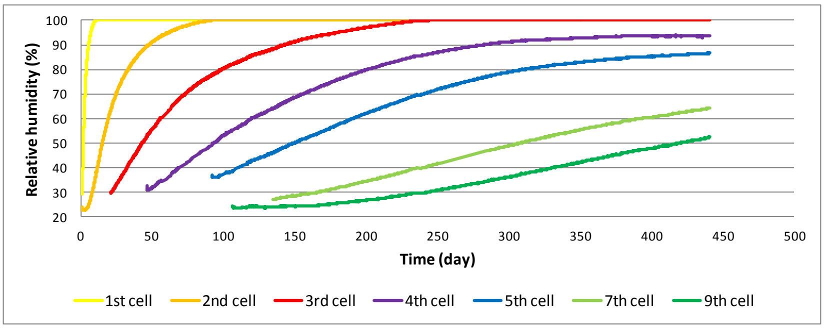

Fig. 3 Development of the relative humidity in different observation points.

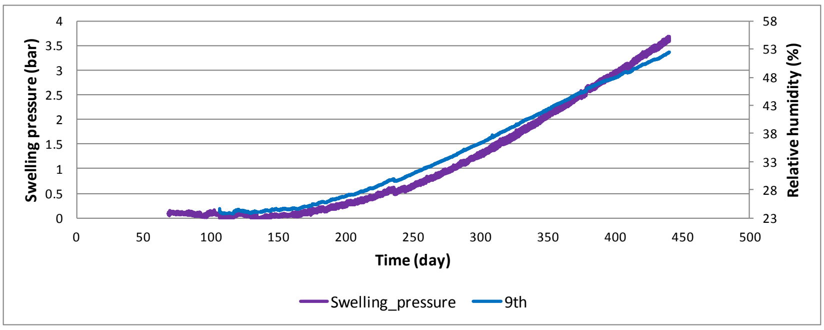

Fig. 4 The comparison of the development of swelling pressure and relative humidity in the 9th observation point.

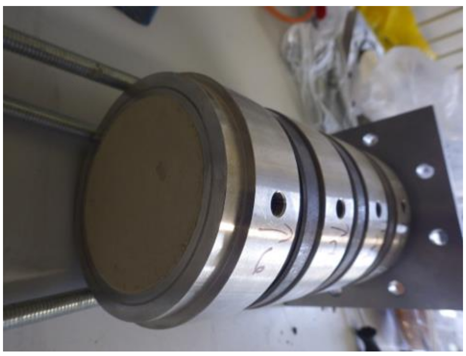

Fig. 5 The dismantling of physical hydraulic model to each cell.

After about 450 days, the saturation of bentonite was terminated and physical model was dismantled into an individual cell (a total of 9 pieces, Fig. 5). 5 cm block of bentonite was extruded from each cell and was cut into approximately 1 cm plates (samples). Subsequently water content of each sample was determined using method of drying sample to constant weight; the resulting values are shown in Fig. 6.

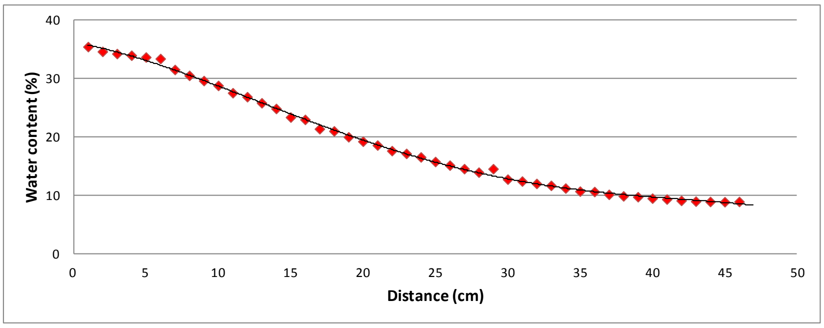

Fig. 6 Profile of mass water content in the PHM, distance indicates the sample position from PHM edge.

The comparison of Fig. 3 and Fig. 6 shows that although the RH sensors show a value of 100%, the material is not fully saturated. This is due to the principle of functionality RH sensor. The sensor is not capable to measure material in a state close to its full saturation (Villar, 2007). Fig. 6 shows a gradual distribution of moisture, when the state of the material at the beginning of the PHM is controlled by the condition/state of the material at its end.

The moisture retention curve was determined from the measured values of relative humidity (after conversion to suction pressure) and the corresponding water content, which was compared with the retention curve obtained by using the block method (Villar, 2007, Fig. 7). The results indicate, that despite the difference in scale (sample in the block method has a volume of about 53 cm^3, volume of one cell in PHM was about 251 cm^3), both retention curves are very well comparable.

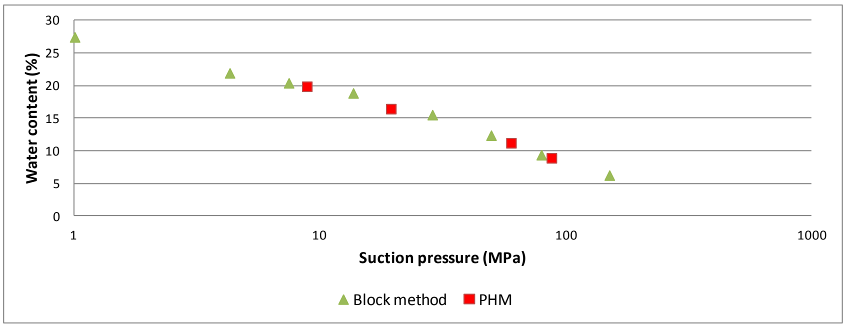

Fig. 7 Comparison of retention curves of bentonite B75 obtained by block method (Villar, 2007) and after dismantling of the physical hydraulic model.

Physical hydraulic model with bentonite pellets has the same geometry as a PHM with bentonite powder. To ensure gradual saturation along the entire 45 cm sample, model contains in the first cell 5 cm thick layer of bentonite powder compacted to dry bulk density 1400 kg/m^3, which will protect the filling of void spaces among pellets by pressure water. Bentonite pellets were placed in the second to ninth cell. The resulting data are illustrated in Fig. 8 to Fig. 10. The same processes as in PHM with bentonite powder are observed.

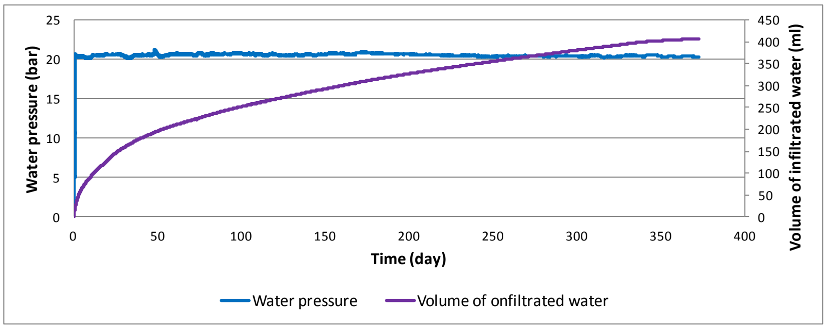

Fig. 8 The pressure and volume of water infiltrated into the sample.

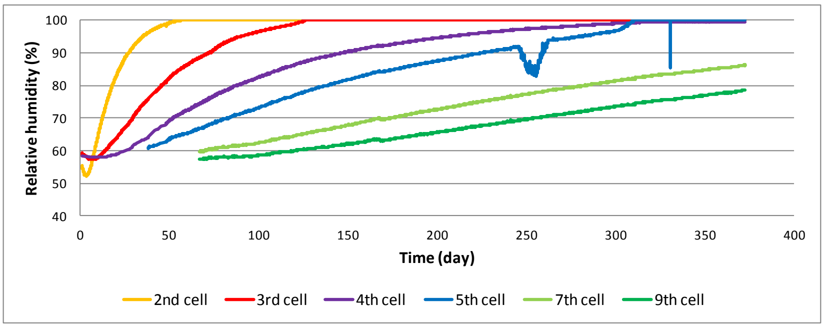

Fig. 9 Development of the relative humidity in different observation points. The sensor in the fifth observation point was damaged during the experiment.

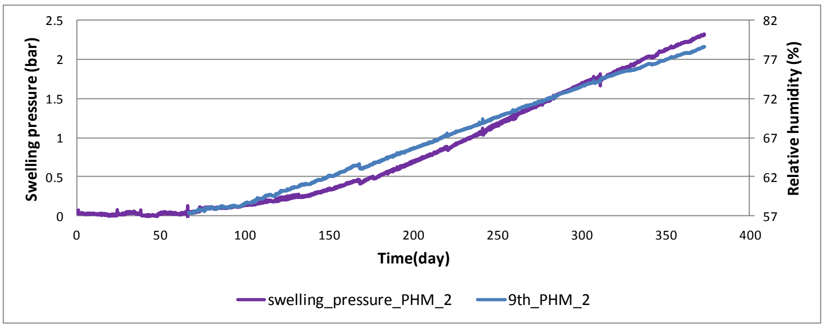

Fig. 10 The comparison of the development of swelling pressure and relative humidity in the 9th observation point.

After a period of around 380 days, the saturation of the bentonite was terminated and the physical model dismantled. Subsequently, the water content of each sample was determined; the results are shown in Fig. 11.

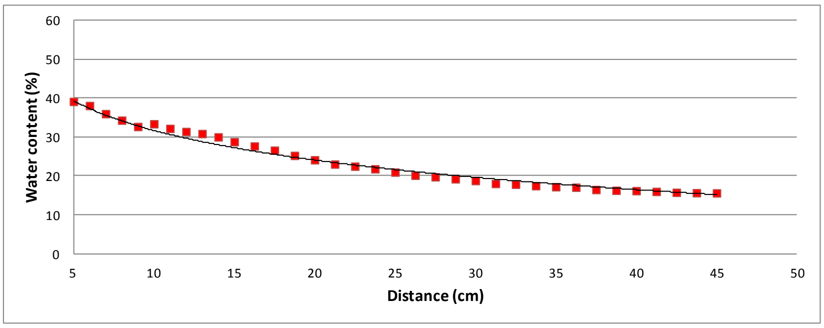

Fig. 11 Profile of mass water content in the PHM with bentonite pellets, distance indicates the position of the samples from the beginning of the physical model

6. Conclusions

Physical models gave data for the calibration of numerical models, when the model parameters were calibrated with aim to achieve the best possible agreement between the measured and model results. The calibrated parameters were then used for predictive modeling, when the most important question was to predict the expected time necessary for whole saturation for 45 cm long bentonite sample. According to the model prediction, the time saturation of the whole sample would take 2992.4 days in the case of the sample with bentonite powder and 1833.8 days in the case of the sample with bentonite pellets.

7. Acknowledgement

The research is being funded from the European Union European Atomic Energy Community (Euratom) Seventh Framework Programme FP7 (2007-2013) according to grant agreement no. 323273, the DOPAS project.

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DOPAS EPSP Experiment Monitoring

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The Experimental Pressure and Sealing Plug (EPSP) experiment being undertaken by Czech Technical University (CTU), SÚRAO and ÚJV a.s. at the Josef underground research centre (URC) and underground laboratory in the Czech Republic as part of the DOPAS project ("Full-Scale **D**emonstration **O**f **P**lugs **A**nd **S**eals").
The EPSP plug has been designed as a prototype plug for a future Czech deep geological repository. The plug has been designed as a multilayer system consisting of two main structural elements which ensure the overall stability of the system, i.e. concrete blocks and a sealing element - a bentonite section positioned between the concrete blocks. The plug is tested by means of injecting air/water/a suspension into a pressurizing chamber followed by the monitoring of the performance of the plug.
The primary aim of monitoring of EPSP is to investigate the various processes underway inside each plug component, to verify component behaviour and to assist in assessing their performance in order to build a knowledge base for the construction of a future repository plug.
The key processes and locations inside EPSP have been identified and sensors have been specially selected in order to capture them. Monitoring of EPSP focuses on water movement inside the experiment and the experiment's response to pressurisation.
An integral element of the monitoring process consisted of the presentation of the measured data for further analysis; therefore the data were instantly available online to end-users via a simple web interface.

1 Introduction to EPSP

EPSP is not a specific DGR plug or seal; rather it was built at a similar scale to a disposal tunnel plug and will contribute specifically towards the development of a reference design for such structures. The objective of the EPSP experiment is to test both the materials and technology to be used for implementation, not to test the design and performance of the reference disposal tunnel plug. At this early stage in the Czech geological disposal programme (Pospíšková 2008, SÚRAO 2011), more than 50 years prior to the scheduled commencement of operation, it is considered by those involved 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.
The conceptual design for EPSP experiment includes the following components:

- 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 pressure chamber is sealed with a waterproofing finish.

- Concrete Walls: Concrete walls (made of blocks) were used to facilitate the 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 forms one of the sealing components of EPSP and was constructed using sprayed glass-fibre concrete. The concrete is of relatively low pH.
- Bentonite Pellets: The bentonite pellet zone comprises “Bentonit 75”, i.e. a Czech natural and high-smectite content Ca-Mg bentonite. The purpose of the bentonite is to seal and absorb/adsorb any water that leaks across the inner concrete plug. The bentonite zone is 2m long. (more in Vašíček et. al., 2016 and Večerník et. al., 2016)
- 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 designed to hold the other components of EPSP in place. However, should the direction of pressurisation of EPSP be reversed, the outer concrete plug have to perform as well as the inner concrete plug, and, therefore, the requirements are the same as the requirements on the inner concrete plug.

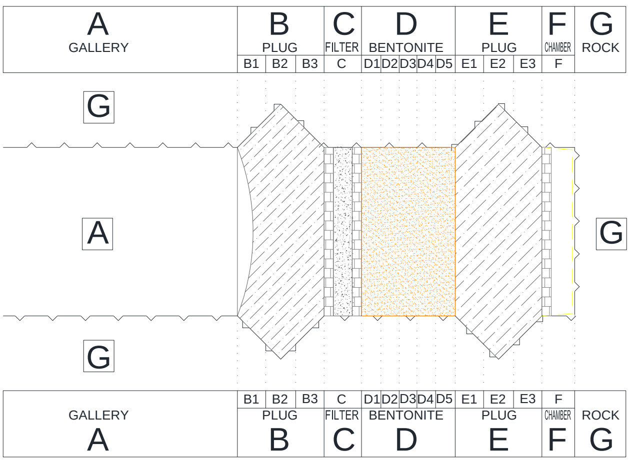

Figure 1 - Scheme of EPSP (measurement profiles)

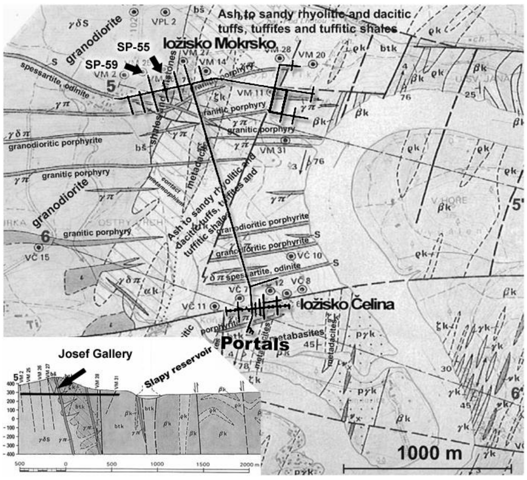

Figure 2 – EPSP location in Josef URL

2 EPSP Location

The EPSP experiment has been built in the Josef Underground Laboratory (Josef URL). The EPSP experiment itself is located inside M-SCH-Z/SP-59 experimental gallery niche. The niche was reshaped in advance and surrounding rock has been improved by grouting in order to reduce the water permeability (in order to allow for higher pressures loaded on the plug itself).

The necessary technology for the experiment is located in parallel niche M-SCH-Z/SP-55.

The niches are interconnected by cased boreholes equipped with tubing for pressurization media circulation (4 leading into filter and 4 leading into pressurization chamber) and for monitoring (5 boreholes equipped with sealed cables lead troughs).

More in Svoboda et al., 2016, DOPAS Seminar, DOPAS EPSP experiment.

3 Monitoring of EPSP

The primary aim of monitoring of EPSP is to investigate the various processes underway inside each plug component, to verify component behaviour and to assist in assessing their performance in order to build a knowledge base for the construction of a future repository plug.

The key processes and locations inside EPSP have been identified and sensors have been specially selected in order to capture them. Monitoring of EPSP focuses on water movement inside the experiment and the experiment's response to pressurisation.

Water movement inside the experiment is monitored in terms of water inflow, water content distribution within the bentonite seal and water (pore) pressure distribution.

The mechanical response of the plug is monitored by means of strain gauges installed at key locations in the concrete plugs and instrumented rock bolts positioned within the rock. Moreover, contact stress measurement is deployed between the rock and the plug.

Temperature distribution is monitored since it is important not only to understand the hydration heat generated through curing, but it is also used as a reference base for sensor compensation during the loading of the experiment.

An integral element of the monitoring process consisted of the presentation of the measured data for further analysis; therefore, the data were instantly available online to end-users via a simple web interface.

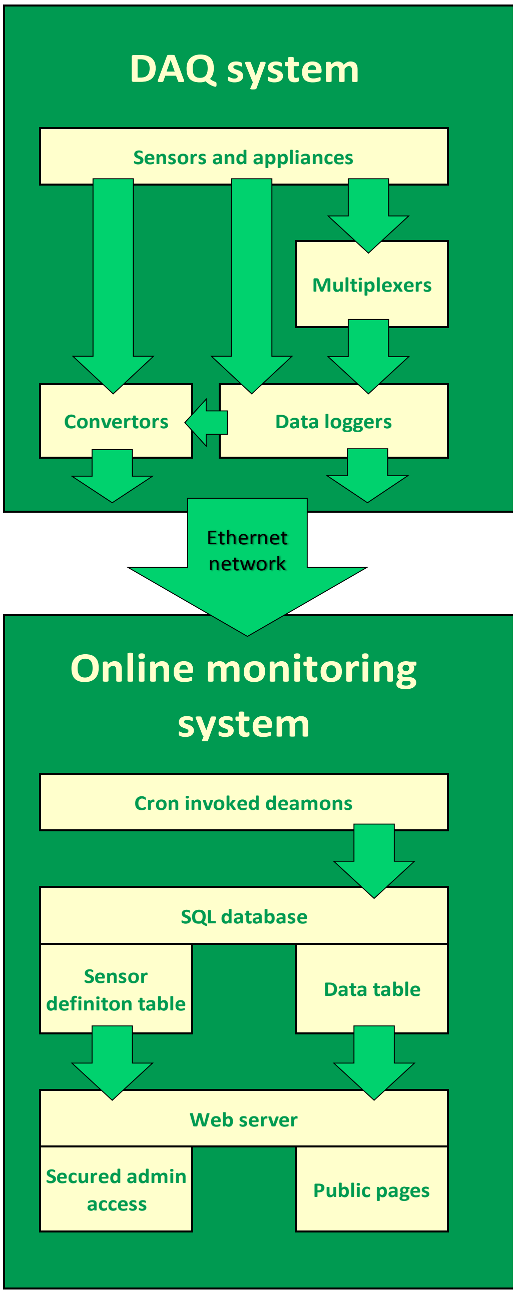

Figure 3 - EPSP measurement system

4 Measurement system

The data acquisition and monitoring systems are based on components previously developed and used at the Czech Technical University in Prague (CTU), Centre of Experimental Geotechnics (CEG) (Pacovský et al. 2006, 2010; Levorová & Vašíček 2012, Vašíček & Svoboda 2011).

The system has two main elements: the data acquisition system (DAQ) and the online monitoring system (Figure 3). The DAQ forms the main hardware element and is responsible for the actual taking of measurements. The online monitoring system is responsible for data collection, storage and presentation to end-users.

5 Data acquisition system

The data acquisition system (DAQ) is responsible for measurement performance and the preparation of data for the monitoring system.
There are two key components: the sensors and the data loggers/convertors.

5.1 Sensors

The sensors used for DOPAS EPSP were selected to capture important processes inside the experiment – with focus to monitor water distribution, pressures, deformation and temperature. Where possible sensors based on different principles were used to measure same phenomena in order to enhance reliability.
Following sensors were used:

- Temperature – digital thermometers DS18B20, analogue LM35DZ and NTC resistors
- Water distribution – relative humidity sensors EE071 and TDR sensors 5TE
- Pressure – VW pressure cells 4810X-10MPa and piezometers 4500SHX-10MPa
- Deformation – VW strain gauges (4200A-2) and instrumented rock bolts (4911-4X)

More over pressurisation technology was monitored including water inflow into experiment.

Figure 4 - temperature sensor in protective housing

Figure 5 - RH sensor including cabling protection

Figure 6 - Sensors ready to be put into assembly

Figure 7 - Cable head preparation

The sensor preparation has been carried out in the workshop of the Josef URC facility. Sensor were assembled and equipped with protective tubing from stainless steel (Figure 4 and Figure 5). Complete assemblies were step by step transported into the underground following the process of plug erection. In the underground the sensors have been installed to their final positions or temporary stored on niche side until their location was ready (and then installed).
In the experiment the sensors are organised into profiles (Figure 1) for easier orientation.

5.2 Data loggers/convertors

Three main types of data loggers are being used in the DAQ system:

- Campbell Scientific CR1000-based system
- GeoKon LC2x16
- CTU in-house built data loggers for digital thermometers

Moreover, several media convertors are being used to connect the digital sensors directly into the DAQ network.

6 Online monitoring system

The online monitoring system has been designed as part of the CEG's DAQ and monitoring system. From the point of view of hardware, it consists of a heterogeneous collection of various sensors, data loggers, network infrastructure and servers on top of which is located the software stack which features two main components: the backend and frontend. Mainly open source programs are used within the system.

6.1 Backend

The backend is responsible for data collection and storage. Data collection is handled by a set of daemons each of which is custom built to fit a specific data logger or digital sensors/equipment. These daemons are responsible for data collection, data format transformation and storage in the open source MariaDB SQL database. They typically run at 10-minute intervals (using Cron) so as to ensure the collection of the very latest data.

6.2 Frontend

The frontend is the most visible part of the system since it is the part with which the user interacts. The frontend is web based and runs on an nginx (http://nginx.org/) web server; it consists of a specialised web site written in the php programming language and JavaScript.

The system pulls all the necessary data from the backend database and presents it to the user. The system rapidly calculates results for the user from the raw data. The results of calculations are cached and held in a separate database in order to speed up the system and to reduce system processing power requirements; this significantly reduces system overheads.

The website provides online information on the status of the experiment and the simple data visualisation interface (2D charting and 3D visualisation). For more comprehensive analytical purposes direct data export is available using specialised URLs.

7 Monitoring performance

Performance of monitoring equipment during construction works and bentonite emplacement was good. The monitoring system has been able to reliably monitor hydration heat evolution and shrinkage of the concrete plugs.

During the pilot test and subsequent run, the instrumentation performed well too. It was able to reliably track the development inside the experiment especially in the sealing section.

Cabling perpendicular to the experiment axis helped to reduce the negative influence of possible flow along cabling.

There have been some problems with water leakage into sensors during 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 already fulfilled their primary purpose (hydration heat monitoring), 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 erection process was mostly negative (but manageable). The fixed cabling creates obstacles for the sprayed concrete. This could lead into the creation of "shadows", e.g., weaker parts behind the obstacles. This could 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 acts as some sort of reinforcement of the plug (although very minor).

8 Conclusions

Monitoring is important part of every experiment as it provides insight into what is going on. Properly designed and maintained monitoring system is therefore essential to get valuable data. The monitoring system itself has influence on the experiment itself and it is very important to design monitoring in such a way that the impact is minimised. That includes not only impact on experiment performance itself but also to experiment construction process.
Reliability and precision of system is another important point. For the EPSP this has been achieved by redundancy and careful selection of sensors types complementing each other. This allowed to cross check the data between sensors of different principles.
It also proved to be important to start monitoring before the construction itself. This way a correct baseline state is captured and experiment implementation has been monitored. The data coming from the experiment provide important basis to the evaluation of the EPSP performance.

9 Acknowledgement

The research leading to these results has received funding from the European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013 under grant agreement no 323273, the DOPAS project, and form Czech Ministry of education, youth and sports under grant agreement no 7G13002.

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POPLU Requirements, Design and Construction

Petri Koho, Petri Korkeakoski

Posiva Oy, Finland

POPLU deposition tunnel end plug test was performed in the demonstration area of ONKALO URCF at the level of -420 meters. The work included the identification of requirements for the experiment, design and test planning including instrumentation and monitoring, material development, tunnel and plug slot excavation including site selection and the construction of the experiment.

POPLU structure and performance expectations are defined in accordance with Posiva’s requirements system where plug-specific requirements are given for Levels 3 (Performance Targets) to 5 (Design Specifications). Some of the specifications are undergoing revisions and some are applicable to only the Posiva's reference plug and not the POPLU alternative design.

The design of the experiment included the structural design of the experiment including the main component of concrete wedge. Materials development was done during the design phase especially for the low-pH concrete used in the concrete wedge and the low-pH grout used to contact grout the interface between the concrete wedge and rock. All the materials used in the experiment were subjected to the foreign material acceptance process of the future repository location of ONKALO. The instrumentation, data acquisition, pressurisation and leakage monitoring systems were designed in order to monitor experiment's behaviour when pressurised to 4.2 MPa.

Two demonstration tunnels numbered 3 and 4 were excavated for the experiment at -420 m level in the demonstration area in ONKALO. The slot for the concrete wedge was produced in demonstration tunnel 4 with drill-wedge-grind method after the tunnels had been approved for use. Three lead-though holes were drilled for the lead-through pipes that carry the instrumentation cabling and pressurisation pipes from one tunnel to the other. Demonstration tunnel 3 was equipped with pressurisation, monitoring and data collection systems. The construction of the experiment in demonstration tunnel 4 included several stages such as the tunnel back-wall casting, filter layer installation, lead-through pipe installation, instrumentation installation, concrete wedge construction and casting. The construction activities ended with the contact grouting of the concrete wedge and rock interface.

POPLU Pressure Testing and Performance

Petri Korkeakoski, Petri Koho, Kimmo Kemppainen, Antti-Jussi Kylliäinen

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The POPLU experiment will be evaluated for leakage and performance by the use of pressurization, to simulate the expected lifetime operation of a deposition tunnel end plug (100 years). The pressurization level has been targeted to be at least 4.2 MPa, representing the hydrostatic pressure at 420 metres underground. The pressurization was started after the concrete plug and components were emplaced and had gained sufficient strength as expected from the structural design. This includes both the concrete plug section castings as well as the injection grouting of the concrete-rock interface.

POPLU pressurization was done according to the pressurization plan until 10 bar pressure was achieved when small leakages were identified from grouting tubes, instrumentation wires and concrete-rock interface. During the following week the leakage decreased almost to half and pressure was increased to 12 bars. This increased the leakage which still stayed under preset limit of 0.1 l/min. Again the leakage decreased during the monitoring and the pressure was increased to 14 bars. This resulted in leakages over the preset limit and the pressurization was stopped and planning of actions to improve the tightness of the plug was started

To test possible wedging effect a fast pressure increase test was initiated. Before the test the plug was pressurized to 10 bars during which it was deaired. After this the pressure was increased as fast as possible to 42 bars. This was achieved in the following 24 hours. During pressurization total leakages increased and in the end were just under 10 l/min. Displacement sensors were indicating possible movement of the plug and to confirm this observation a series of rapid pressure changes were performed (42 bars - 5 bars - 42 bars). Each pressure increase was faster than previous, last one taking less than one hour to reach 42 bars. After this last increase the total leakage was about 2 l/min. Displacement sensors were showing movements during each pressure change, but the data needs to be thoroughly analysed before final conclusions.

Hydraulic Sealing Ability of Bentonite Pellet Filling at Small, Contact Apertures

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Saturation of the clay-based, barrier components in the repository for spent nuclear fuel at Olkiluoto will be governed by the hydrogeological conditions in the surrounding bedrock and the hydraulic properties of the components themselves, and may result in the formation of channels or pipes through the buffer or backfill material, and possibly erosion thereof, inside the deposition tunnels.

After the available void volume inside the deposition tunnel has been filled, but the central tunnels remain open, the water pressure gradient will be transferred from the initial inflow point to the tunnel plug (see Figure 1). Ideally the inflow will effectively cease and homogenization will take place. However, leakage may occur at a variety of downstream interfaces, e.g., other fractures, fissures, or joints, as well as the deposition tunnel plug itself leading to undesired water flow and the possible preservation of advective transport pathways.

Insofar as any deposition tunnel material may be able to seal leakages due to a “self-grouting” or ”self-filtration” effect, such outflow may be stopped altogether. Given the heterogeneous design of the tunnel backfill installations, it is reasonable to assume that the material in most direct contact with possible leakage interfaces will be the outermost foundation layer material, pellet-filling materials and plug components.

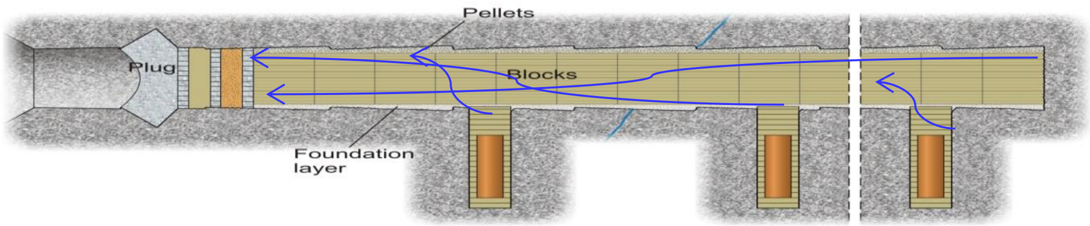

Figure 1. *Schematic figure showing a deposition tunnel and various saturation inflow scenarios (Keto et al. 2013).*

In order to evaluate the sealing potential of bentonite pellet material at small leakage apertures, a series of laboratory experiments were performed in which pellets of different materials and shapes (Wyoming bentonite, roller-compacted pillows and disks, Wyoming bentonite extruded rods and Milos bentonite extruded rods) were placed into contact with a small, contact leakage slit (Figure 2) and tested against solution salinity, inflow rate and aperture size. Additionally, threshold conditions for channel formation through the pellet volume were examined as well.

For MX-80, roller-compacted, pillow-shaped pellets at a dry density of ~920 kg/m^3, material extrusion into a 0.05 mm leakage slit routinely occurred after the saturation front reached the aperture. Complete sealing of leakage flow was never observed up to the maximum inflow pressure of 4000 kPa. However, periodic inflow, lower inflow rates, possible buildup of accessory minerals in the leakage slit, higher initial dry density of the pellets and smaller aperture size were observed to enhance the sealing ability, i.e., resulted in higher inflow pressures to maintain leakage outflow.

In sealing tests with MX-80 pillow-shaped pellets, immediately after the available void volumes were filled, distinct and sustained flow channels were formed at 0.01 L/min inflow rate and higher with 10 g/L TDS solution (Figure 3, column C). At flow rates of 0.1 ml/min and down to 0.0055 ml/min in tests against 10 g/L solution channel formation was not observed (Figure 3, column B). At similar inflow rates against tap water solution, water pocket formation was observed and the systems were "sealed" to the permeability of the pellet medium (Figure 3, column A).

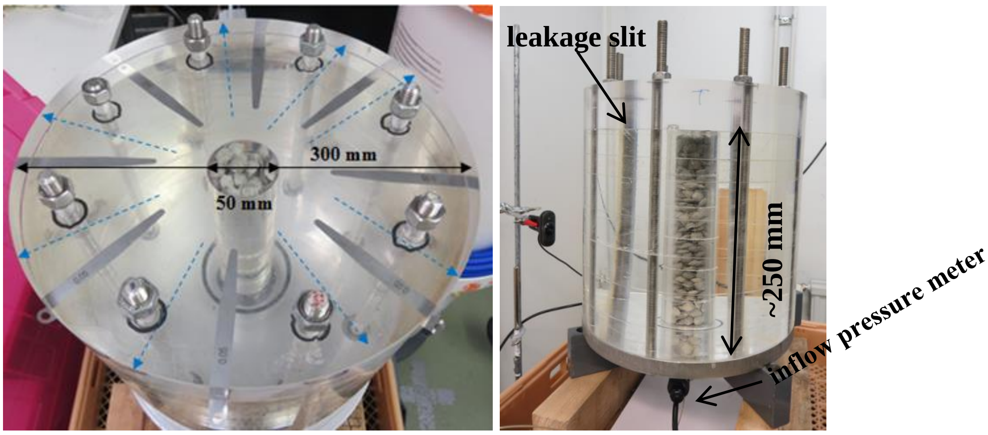

Figure 2. *Photographic images of the sealing test system. Overhead (left) and facing (right) images of the test setup after material installation. Blues dashed arrows show the direction of leakage outflow.*

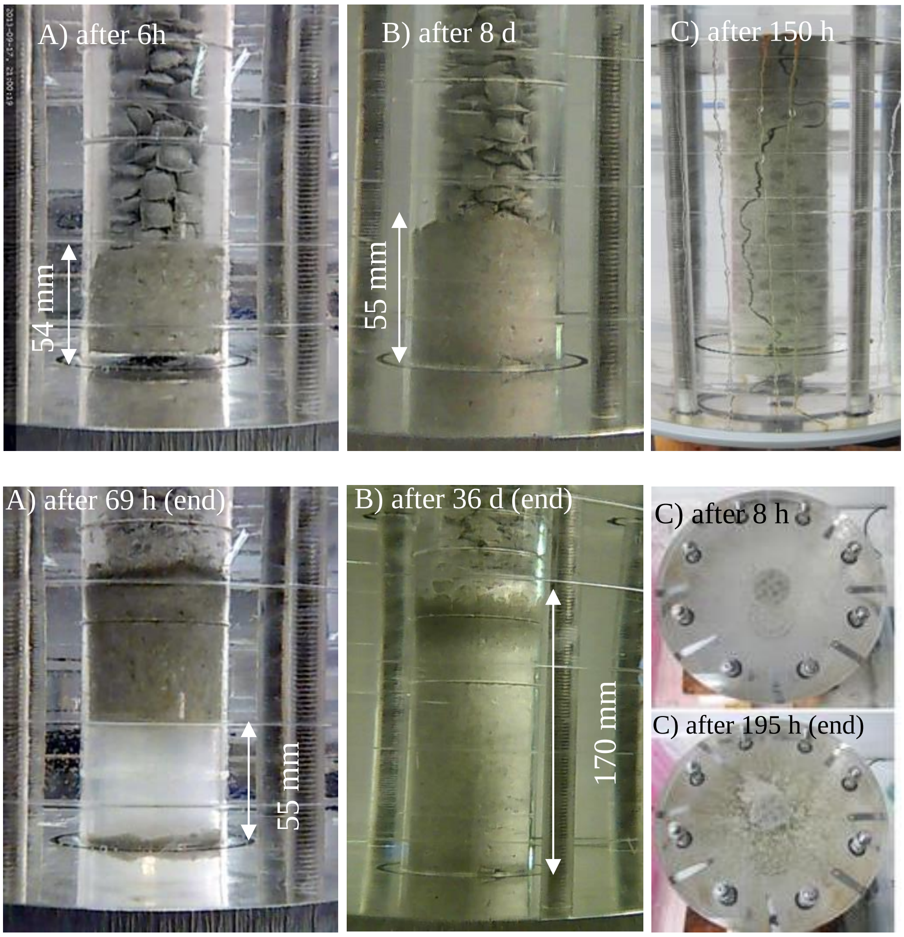

Figure 3. *Photographic images of three sealing tests with MX-80 pillow-shaped pellets: Column A - inflow rate = 0.1 ml/min with tap water, Column B - inflow rate = 0.0055 ml/min with 10 g/L TDS solution, Column C - inflow rate = 10 ml/min with 10 g/L TDS solution.*

Interestingly, completely different behaviour between extruded, rod-shaped (manufactured from Wyoming and Milos bentonites) pellets and roller-compacted, pillow-shaped and disk-shaped pellets (manufactured from Wyoming bentonite) at inflow rates of 0.01 L/min was observed. The latter materials, spanning densities from 919 to 1030 kg/m^3 and solution compositions from 10 - 70 g/L TDS, always gave rise to piping flow channels at the surface of the pellet volumes which were sustained over the course of the tests at inflow pressures below 2000 kPa. The extruded, rod-shaped pellets, on the other hand, show very rapid rises (2 - 4 hours) in inflow pressure to 4000 kPa (maximum for these tests) and sealing of the initial piping flow channels within the first 24 hours of the test.

Absolute sealing (i.e., zero outflow to a maximum pressure of 5 MPa) through wetted pellet volumes in contact with a small, planar leakage interface, potentially as a physical sealing of the leakage interface due to the intrusion of clay material, was not observed for any of the material, density, solution and inflow rate test combinations described in this report. However, it can be stated that sealing to the possible hydraulic conductivities of the pellet medium was observed for the extruded, rod-shaped pellet systems. Effectively, such sealing represents the highest level of potential sealing for any given, clay-based repository component to a non-clay based interface.

The leakage slit is likely an overly conservative interface. Insofar as failures through the tunnel plug may be more pointwise, future sealing tests will focus on smaller leakage features.

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Testing the Influence of Bentonite Sealing Property for Safety of Deep Geological Repository

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Summary
Although the plug itself does not fulfill a safety function sensus stricto, it contributes to the safety function of bentonite sealing layers via keeping the bentonite material in a defined place and preserves it as much as possible in predefined form (mainly in terms of bulk density). The requirement for a minimum lifetime of spent nuclear fuel (SF) container is 10 000 years. During this time, it is assumed that would be no container damage and therefore this time can be considered as a start time in simulations of deep geological repository (DGR) safety assessments. However, by this time the bentonite material will be saturated and could be exposed to an increased groundwater inflow from structures with increased hydraulic conductivity. It might affect bentonite material structure round the SF container. Therefore, it is necessary to consider namely formation of erosion channel in bentonite layer, being washed out. Therefore, the setting of complex model, used for DGR safety assessment in GoldSim program, was changed in order to consider such a damage in bentonite layer. The results show that the state of the bentonite layer has a significant influence not only on the effective dose rate, but also on change in the dominant critical radionuclides.

1. Introduction background

The requirement for a minimum lifetime of SF container is 10 000 years. During this time the bentonite material will be saturated and could be exposed to an increased inflow of groundwater from structures with increased hydraulic conductivity. That might affect the structure of bentonite material around the SF container. Therefore it is necessary to consider the formation of erosion channel in bentonite layer, being caused by washing out bentonite material. Therefore, the setting of complex model, used for DGR safety assessment in GoldSim program, was changed in order to consider such damage of bentonite layer and its influence of complex DGR safety performance.

2. Scope and objectives

The following four variant states of bentonite layer were considered (Fig. 1A):

1. Bentonite material behind plug remains intact; the erosion channel was not created
2. The erosion channel in bentonite material was created: the channel has been filled by material with lower bulk density The erosion channel in bentonite material was created: the channel has remained empty
3. All bentonite was washed out, the void between the plug and SF canister remained empty

Concerning the second and the third variant, several variants of the erosion channel opening were simulated (Fig. 1B). The degree of bentonite layer damage is given by multiplication of the SF containers circumference and percentage of damage.

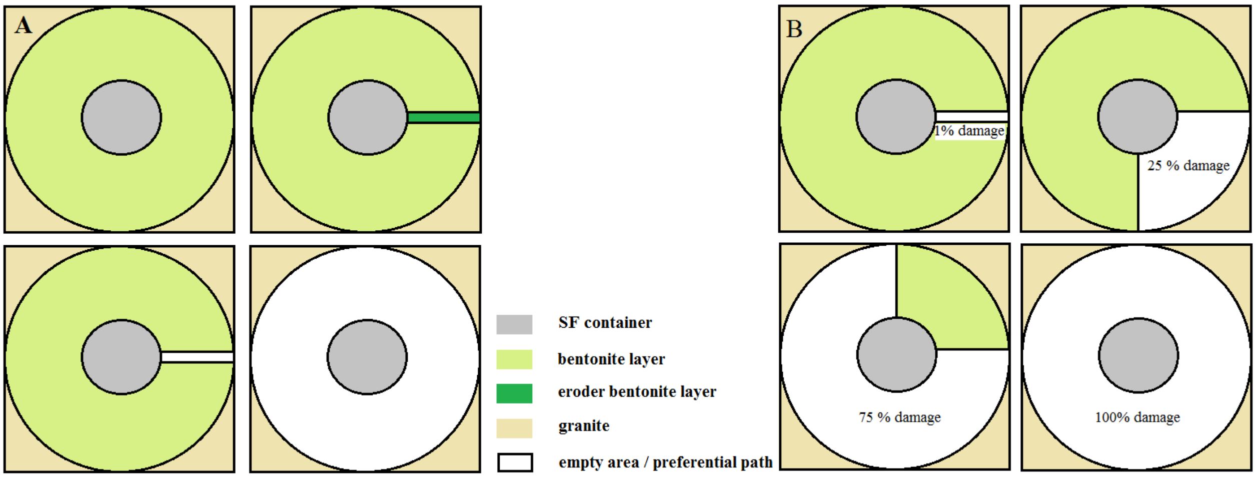

Fig. 1 Four variants of the bentonite layer simulated states (A) and the rate to the bentonite layer damage (B), contemplated in the various simulations.

3. Numerical modelling

3.1 Conceptual model

Czech concept of SNF and HLW (high level waste) disposal generally assumes emplacing SF into the metal containers that are stored in disposal boreholes in the rock massive at the depth of about 500 m below the surface. The model assumes disposal of 6000 carbon steel container. Activity release occurs after SF container degradation of. The SF container degradation is described by a distribution curve obtained by applying the Weibull distribution. Minimum container life-time is 10,000 years, and the median is 110,000 years.

Bentonite layer is modeled by 15 concentric layers. The outer layer represents the interface with the repository surrounding (rock compartment). The rock diffusion layer is modeled at the interface bentonite/ rock compartment in order to eliminate the influence of advection in bentonite layer.

The radionuclides are transported by diffusion through the bentonite layer toward a rock compartment (only model simplification). Rock massive is modeled as a compartment with 3km × 1km × 10 m size. At each time step, the concentration balance is set in this area, meaning that the same conditions prevails in the overall area. Radionuclides from the disposal part are transported by groundwater flow (advection is considered as a transport process) to a preferential path in the geosphere.

Geosphere is modeled using the components "Pipe" (more than one), considering the model transport processes as advection, diffusion into the rock matrix and sorption. From the last "Pipe" groundwater flows into the compartment which models processes in biosphere.

The biosphere is modeled using four compartments representing the land (cultivable and forest), pond and river, and represents a universal model that corresponds to the current lifestyle of the Czech Republic. The output of the biosphere model is the effective dose rate to humans living in the area affected by DGR.

3.2 Results and discussion

The development of the effective dose rate in the case with empty piping channel (variant 3) for various degrees of bentonite layer failure of the is shown in Fig. 2; for the case with filled piping channel (variant 2) in Fig. 3. The contributions of individual radionuclides to the total effective dose rate in case of empty and filled piping channel for different degrees of damage is shown in Fig. 4 - Fig. 8.

The figures Fig. 2 and Fig. 3 show that the effective dose rate grows with an increase rate of bentonite layer damage. The explanation for this phenomenon is based on the loss of material available for radionuclide sorption. In case of a sorption decrease more radionuclides are released directly into the water (increases their concentration in water).

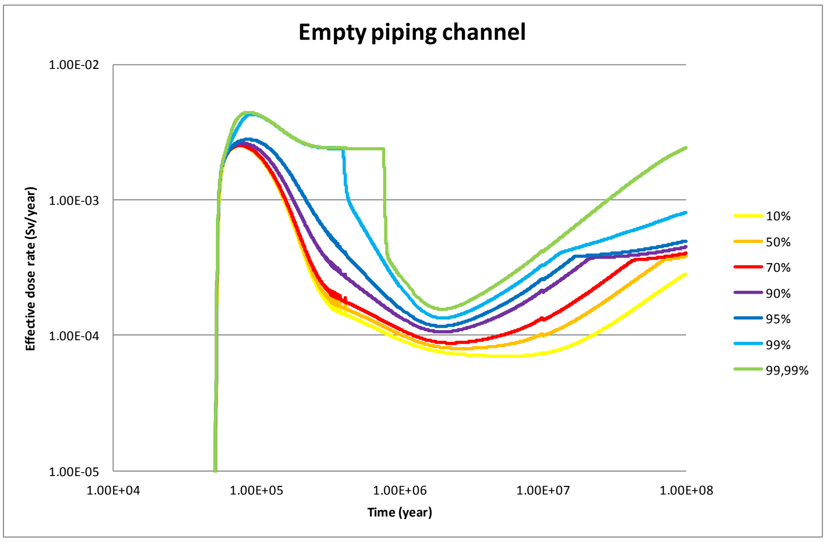

Fig. 2 Development of effective dose rate in the case of empty piping channel consideringr different damage degrees of the bentonite layer.

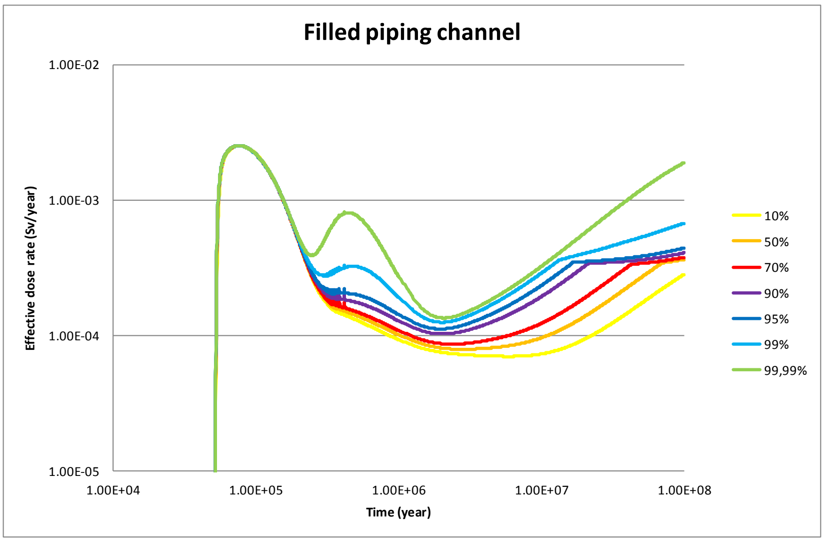

Fig. 3 Development of effective dose rate in the case of filled piping channel, considering different damage degrees to the bentonite layer.

Significant increase of effective dose rate due to contribution of ^{126}Sn can seen in the case of empty piping channel (Fig. 4 and Fig. 5). This contribution of ^{126}Sn is evident also in the case of a filled piping channel, although the release exhibits different trend over time and the effect of ^{126}Sn appears only in the case of higher damage rate of the bentonite layer (Fig. 6 and Fig. 7).

In case of empty piping channel the contribution radionuclides of ^{126}Sn, ^{229}Th, ^{230}Th and ^{242}Pu to the total effective dose increases with the damage degree to the bentonite layers.

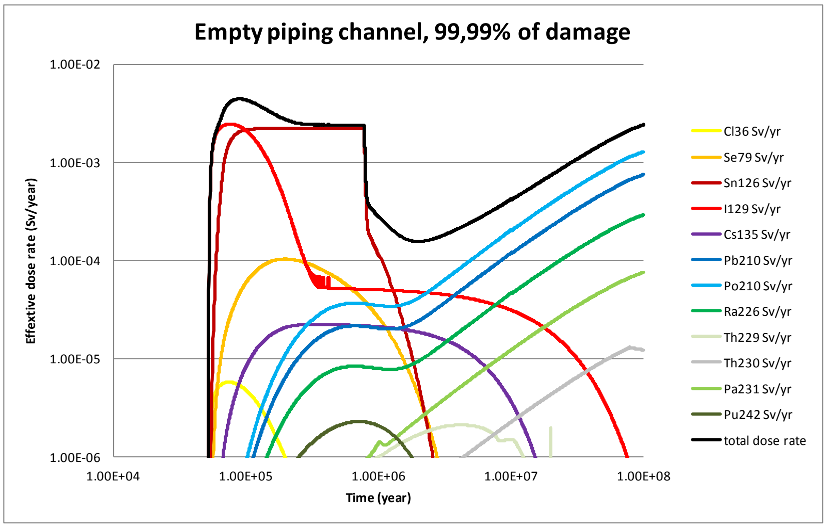

Fig. 4 The contributions of individual radionuclides to the total effective dose rate in the case of empty erosion channel simulating 99.99% damage bentonite layer.

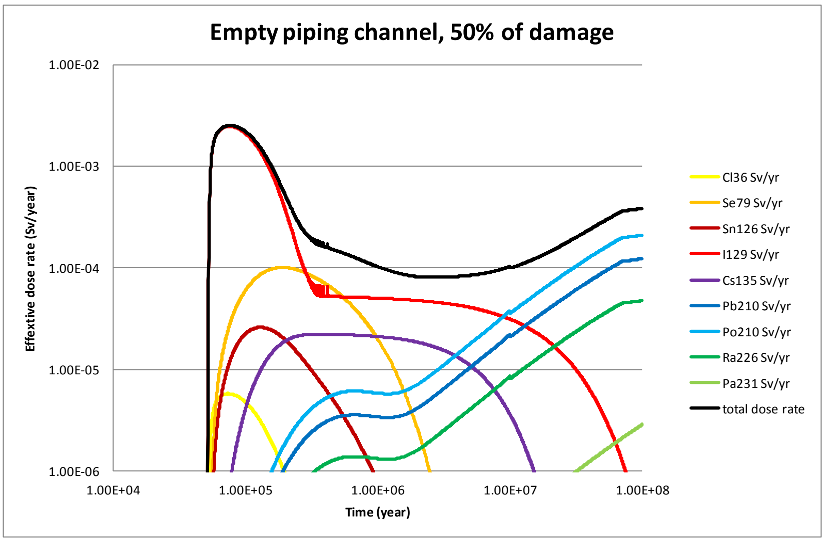

Fig. 5 The contributions of individual radionuclides to the total effective dose rate in the case of empty erosion channel simulating 50% damage bentonite layer.

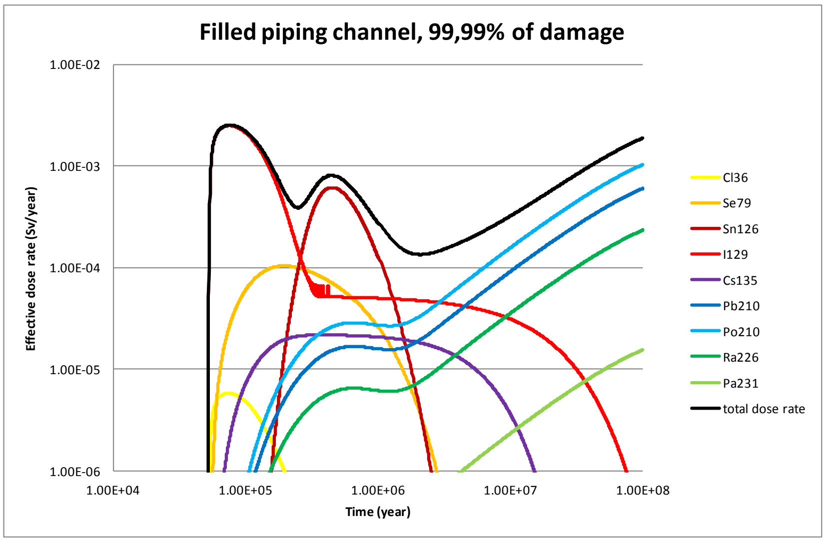

Fig. 6 The contributions of individual radionuclides to the total effective dose rate in the case of filled erosion channel simulating 99.99% damage bentonite layer.

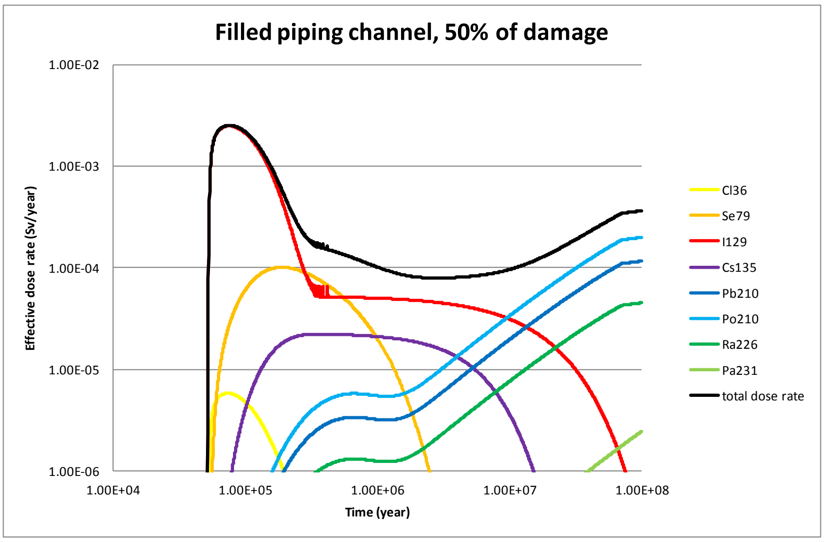

Fig. 7 The contributions of individual radionuclides to the total effective dose rate in the case of filled erosion channel simulating 50% damage bentonite layer.

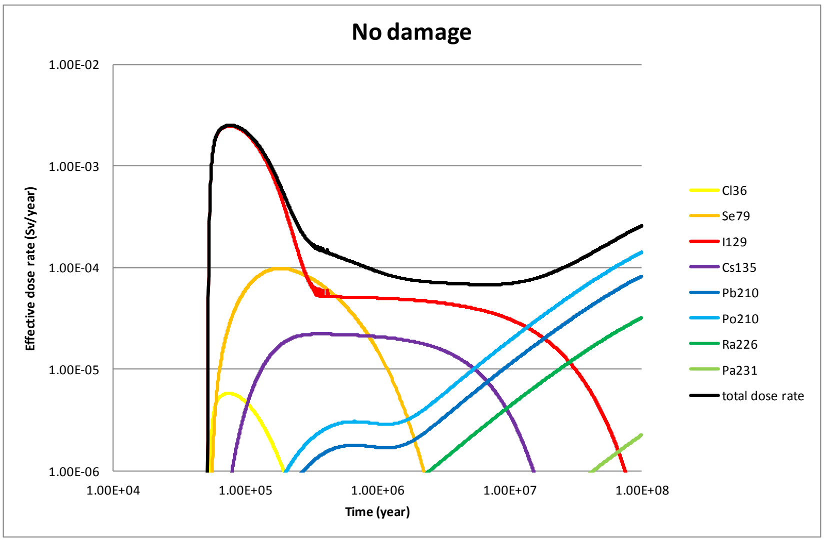

Fig. 8 The contributions of individual radionuclides to the total effective dose rate considering intact bentonite layer.

6. Conclusions

The results showed that the state of the bentonite layer has an influence not only on the effective dose rate, but also on contribution of dominant critical radionuclides. On the other hand, it should be noted that cases with a larger radius of erosion channels are almost unrealistic, being taken into account only for a parametric study. None of the scenarios for DGR safety performance in the Czech Republic considered the washing out of bentonite to such an extent.

7. Acknowledgement

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Compliance Assessment for Plugs and Seals in Germany

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Within the German programme a quantitative approach to compliance demonstration has been developed. This strategy is a semi-probabilistic, reliability-oriented concept using partial factors and is based on the internationally recognized Eurocodes. The general principle of the assessment method is described and an application example for one of the required individual assessments is given for a vertical emplacement borehole seal.

Introduction

The primary objective of repository research is to establish a scientific and technological basis for a safe disposal of high-level radioactive waste. In addition to the technical feasibility, one major goal is the feasibility of suitable safety assessments. In this context, the safety assessments of the multi-barrier system, which consists of the geologic barrier and the necessary geotechnical barriers, e.g., containers and drift or shaft seals, are of major importance. These individual components of the sealing concept, which often are arranged in parallel, are to ensure the safe long-term isolation of the radioactive waste.

Regarding design and safety assessment, the use of a uniform concept for all types of geotechnical barriers is considered to yield the best results. The following sections give an introduction to the partial factor concept. The methodology as relevant to a safety analysis is described quantitatively using exemplarily a sealing element and an abutment for a seal concept for an emplacement borehole recently developed within the scope of the German R&D project ANSICHT.

Compliance Assessment Method

The German strategy for demonstrating compliance of the seal designs with the design basis has been developed by DBE TECHNOLOGY GmbH (Müller-Hoeppe et al. 2012). It is a semi-probabilistic, reliability-oriented concept that uses partial factors and is based on the internationally recognized Eurocodes (EC-JRC 2008). The Eurocodes are a series of ten European standards that each consist of several parts. In engineering, they 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.

In this approach, specific requirements are considered 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 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. Figure 1 shows the general principle of the assessment method called the “partial safety factor method”.

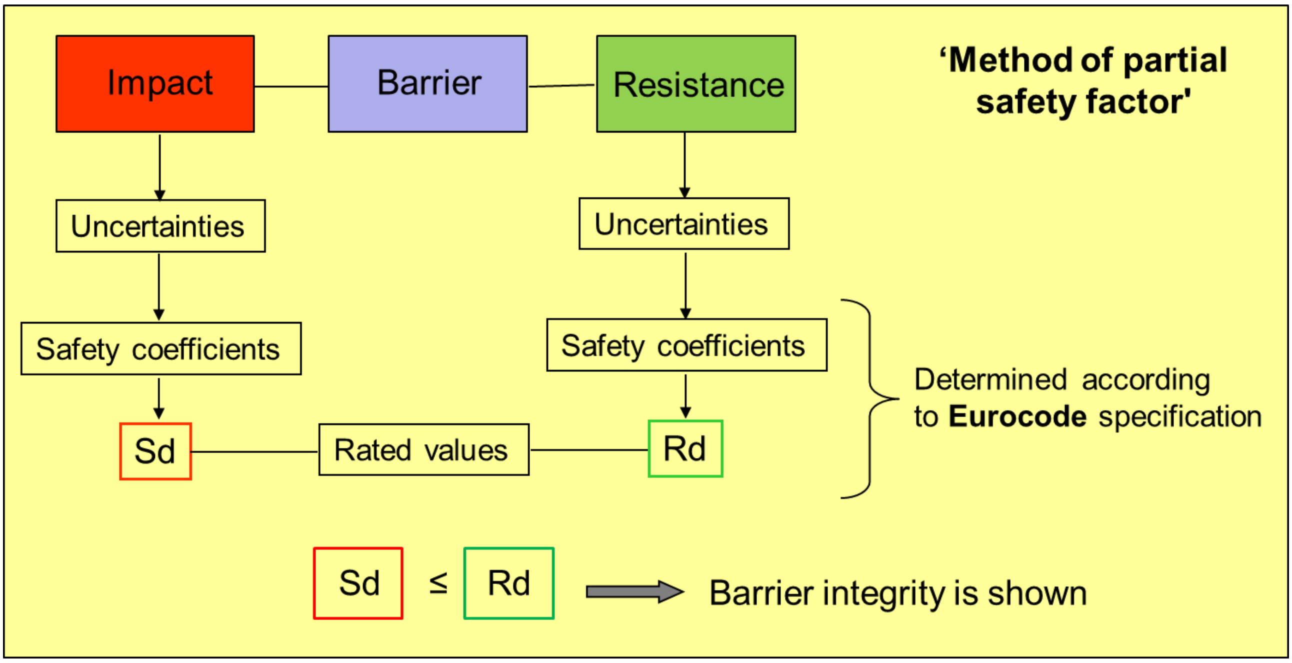


Figure 1: General principle of the partial safety factor method.

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, 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.

The following individual assessments are essential for demonstrating compliance with the design basis according to the state of the art in technology:

- Demonstration of sufficient hydraulic resistance (demonstration of tightness)
- Demonstration of sufficient load bearing capacity (structural integrity)
    - Demonstration of structural stability
    - Demonstration of crack limitation
    - Demonstration of deformation limitation
    - Deformation of filter stability
    - Demonstration of durability

These assessments are essential for demonstrating the effectiveness of a sealing construction and thus the compliance with the design basis. Furthermore, the

- Feasibility

needs to be assessed and demonstrated. Figure 2 shows the individual assessments and their connections to the overall demonstration of functionality. In addition to applying the method of partial factors, a reliability assessment based on empirical data needs to be carried out in order to quantify the reliability of using probabilistic methods.

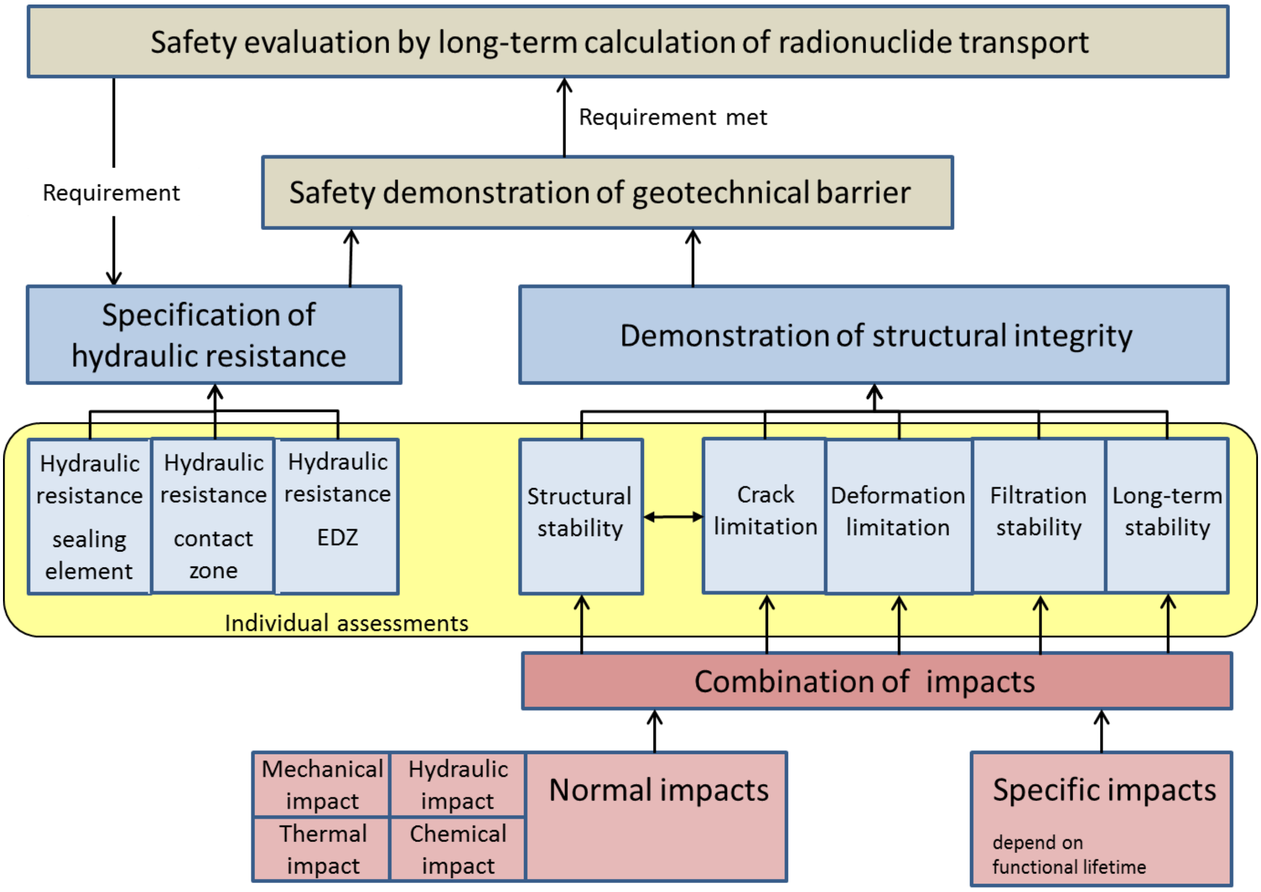


Figure 2: Connection of hydraulic long-term calculations in a long-term safety assessment with the individual, function-related assessments (after Müller-Hoeppe et al. 2012).

The design values for the individual assessments are derived from the characteristic values of the actions on and the properties of the barrier combined with the related partial factors. When applying the method of partial factors, actions and resistances, i.e. the parameters of the targeted relation, are allocated partial factors. The effects of actions are multiplied by partial safety factors and, thus, increased, whereas resistances are divided by partial factors and, thus, decreased. This method and the application of partial factors generally account for uncertainties in the representative values of the actions and uncertainties in the properties of the structure.

Application example

The current German repository design for disposal of heat generating high active waste and spent fuel in huge Jurassic clay formations includes the emplacement of canisters in short vertical boreholes. Each borehole is equipped with different components such as an inner and outer liner, a buffer, and a seal (Figure 3). The seal is located at the top of the borehole consisting of a bentonite element and a concrete abutment. The dimensions of the abutment correspond to the borehole cellar, which is needed for the emplacement. The diameter of the bentonite seal is 2.5 m, with a height of 5 m.

The main function of the borehole seal is the reduction of brine movement inside and out of the borehole. The seal is made of an in-situ compacted mixture of pellets and lose bentonite, in regard to the good experiences collected at Salzdetfurth experiment (Breidung 2002). One pellet has a volume of approximately 10 cm². Overall the pellets create 70 to 80 mass-% of the mixture. The lose bentonite has a grain size smaller than 3 mm. Both components are mixed and compacted in-situ by vibration-compactors. This technology creates dry bulk densities between 1600 and 1800 kg/m³. The final type of bentonite is not known yet. The selection depends on different criteria such as the chemical compatibility to the host rock and the pore water, the needed swelling pressure or the needed permeability. Up to now the Ca-bentonite type Salzdetfurth is considered as reference material. (Lommerzheim & Jobmann 2015)

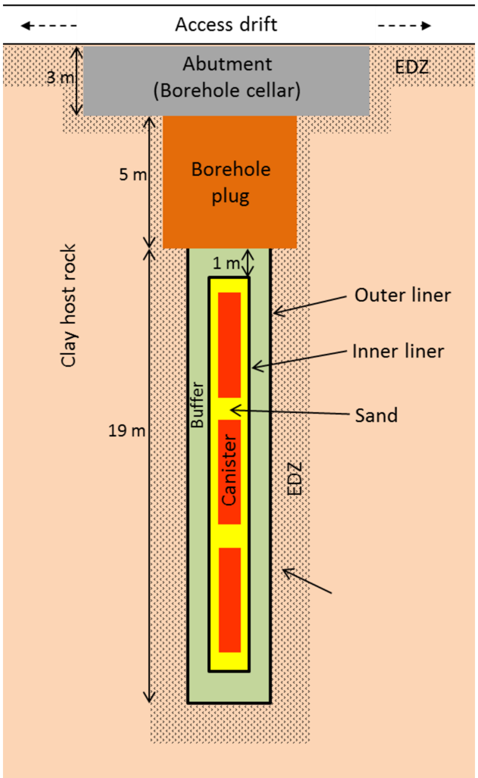


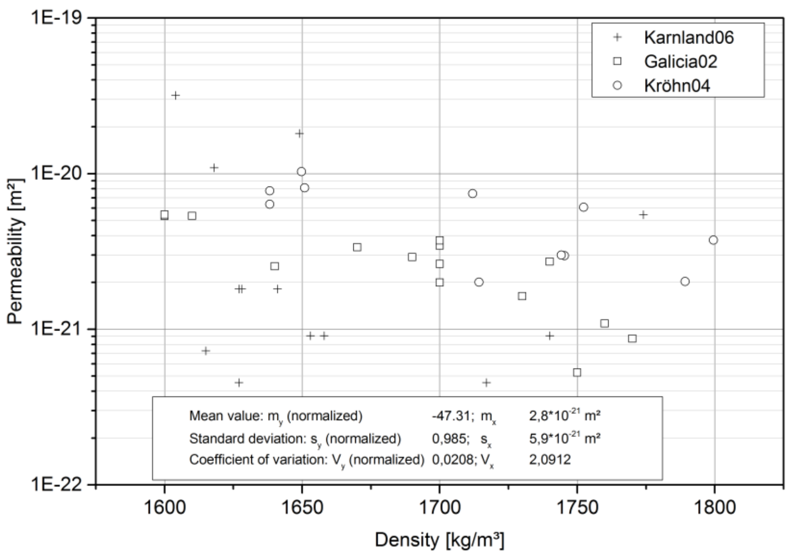
Figure 3:Conceptual design of a vertical emplacement borehole and seal

The bentonite seal must fulfil the evidence of a sufficient high hydraulic resistance, the evidence of crack limitation and the evidences of long-term and filtration stability. The feasibility is already demonstrated by comparable large scale in-situ experiments like the German Salzdetfurth experiment (Breidung 2002) or the Belgian RESEAL experiment (van Geet et al. 2009).

The demonstration of a sufficient high hydraulic resistance includes the specification of the permeability of the seal and the comparison to the design situations. Those create the impacts to the seal. The major design situations are the steady state case, the transient case, extraordinary situation and an earth quake. The exact assessment cases are defined in regard to the site specific FEP-list. The following sections give a brief overview of the demonstration method of partial factors for determination of the permeability at the sealing location.

The specification of the permeability (K) at the sealing location includes the seal (S), the contact interface (C) and the EDZ. The permeability of all three parts is called integral permeability (K_{int}) of the seal location:

$$K_{int} = \frac{K_S * A_S + K_C * A_C + K_{EDZ} * A_{EDZ}}{A_S} \qquad \text{Eq. 1}$$



This demonstration method bases on a sufficient amount of necessary data. Within this exemplary evidence a data set is created from different references (see Figure 4). From those data the permeability of the seal can be calculated in dependency of the dry density.

Figure 4: Permeability of the saturated bentonite samples in dependency of the dry density, based on (Jobmann et al. 2016)

The data set allows the estimation of the design value (X_d). The Eurocode (EN 1990) provides the determination of the design value by the characteristically value as the preferred method (Eq. 2). This approach includes the assumption that the data are normally distributed. The determination is realized with a logarithmically normalized data set. Uncertainties are covered by the use of a partial factor (γ_m) and the fractile factor (k_n). The conversion factor (η_d) considers uncertainties out of the data transmission between different scales (laboratory, half or full scale).

$$X_d = \frac{\eta_d}{\gamma_m} * e^{[m_y - k_n * s_y]} \qquad \text{Eq. 2}$$

In addition the Eurocode describes the method for determining the design value directly or as an estimation of the average value using a high confidence interval of 95% (see Eq. 3 and 4).

$$X_d = \eta_d * e^{[m_y - k_{d,n} * s_y]} \qquad \text{Eq. 3}$$

$$X_d = \frac{\eta_d}{\gamma_m} * \left[m_x - \frac{t_{(n-1)}^{0,95} * s_x}{\sqrt{n}} \right] \qquad \text{Eq. 4}$$

Due to the absence of reliable exploration data the expanse and the permeability of the EDZ have to be estimated, too. Wagner (2005) gives a simple approach for the estimation of the EDZ`s depth. Here it is expected to be 0.8 m. This corresponds to an area of 9.6 m². The permeability of the EDZ was deduced from Major et al. (2005). Table 1 summarizes the individual and integral permeability based on the different calculation methods.

Table 1: Overview of the design values based on the different determination methods

Design value by…	**Seal**	**Contact area**	**EDZ**	**Total**
…characteristical value	$1.2 \cdot 10^{-20}$	neglected	$9.2 \cdot 10^{-19}$	$\mathbf{2.5 \cdot 10^{-20}}$
…direct determination	$6.9 \cdot 10^{-20}$	neglected	$1.7 \cdot 10^{-15}$	$\mathbf{2.5 \cdot 10^{-17}}$
…estimation of the average value	$3.4 \cdot 10^{-21}$	neglected	$1.7 \cdot 10^{-19}$	$\mathbf{5.9 \cdot 10^{-21}}$

The expected permeability at the seal location is almost comparable with the permeability of the undisturbed host rock. This allows the conclusion that the seal will have a sufficient low permeability. Nevertheless, the exemplary demonstration includes several assumptions. A reliable assessment calls for a sound data base which is not yet available and a comprehensive knowledge of the rock at the seal location. The comparison of the three determination methods shows a significant difference between the direct determination method and the other two methods. This results mainly from the limited data available for the EDZ and the currently high fractile factor $k_{n,d}$.

Conclusion

The German strategy for demonstrating compliance of the seal designs with the design basis is a semi-probabilistic, reliability-oriented concept that uses partial factors and is based on the internationally recognized Eurocodes. Specific requirements are considered to have been met if the designs meet criteria (limiting values) evaluated by means of “assessment cases” (or load cases). 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. The application example regarding the seal tightness shows how the compliance assessment method works but also that a sound data base is required to yield consistent and reliable result.

Acknowledgements

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Reactive Transport Modelling of Bentonite Shaft Seals under Hypersaline Conditions

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1. Introduction / Background

Bentonite is a widely considered sealing material for radioactive waste repositories (e.g., Madsen, 1998; Wilson et al., 2011) and its behaviour has been studied in a variety of settings. Ontario Power Generation's Deep Geological Repository (DGR) design for low and intermediate level radioactive waste would be constructed about 680 m below ground surface. The host rock of the DGR is the Cobourg Formation (limestone) of Ordovician age. This formation is overlain by about 200 m of shales (Georgian Bay Shale), and a further 400 m sequence of predominantly argillaceous formations. The DGR shafts will be sealed primarily with a 70:30 bentonite/sand mixture, although there will be a concrete monolith at the level of the DGR and shallower concrete bulkheads to provide mechanical support as well as an initial low-permeability barrier.

In this study, the long-term durability of the bentonite in contact with sedimentary wall rocks of the shaft and highly-saline porewater was assessed. Interactions around the secondary concrete sealing materials in the shaft were assessed separately (Quintessa, 2011).

Groundwaters in the Georgian Bay Shales are expected to be highly saline and Mg-rich. The possible significance of reactions between bentonite and such waters for the sealing properties of bentonite have hitherto received less attention than reactions such as smectite illitization, iron-bentonite interactions and cement-bentonite interactions (e.g. Metcalfe and Walker, 2004; Karnland and Birgesson, 2006; Savage et al., 2007; Wilson et al., 2011; *inter alia*).

Experimental studies on the interaction of bentonite with saline solutions and brines with a wide range of salinities and pH show that ion exchange occurs within the bentonite and that smectite persists as the dominant type of clay mineral over laboratory timescales (Kaufhold and Dohrmann 2009; Herbert et al. 2008; Suzuki et al. 2008). Based on TEM-EDX analyses of the samples, Herbert et al. (2008) report changes in layer composition and suggest that ultimately, smectite could be altered to non-swelling minerals such as kaolinite or pyrophyllite. Natural analogue studies can yield more detail on the possible long-term effect of these interactions. Studies of bentonite-seawater interaction (Fernández et al. 2005; Pérez del Villar et al. 2005) have shown little, if any structural modification of smectite layers due to saline water intrusion. However, natural analogue studies for bentonite-hypersaline fluid interactions have yet to be identified.

The potential for alteration of the bentonite/sand mix due to interactions with the Georgian Bay Shale groundwaters over performance-relevant timescales of up to 100 000 y was investigated using reactive transport models. Reactive transport modelling activities were informed by the development of activity diagrams to help understand the stability of the clay minerals.

2. Concept and Model Details

A schematic representation of the region around shaft-rock system is shown in Figure 2-1. The dimensions shown correspond to the ventilation shaft, rather than the wider main shaft in the DGR, as the smaller diameter shaft has less sealing material and therefore a greater potential that alteration will affect performance. An Excavation Damaged Zone (EDZ) is expected to a depth of 1.1 m around the shaft.

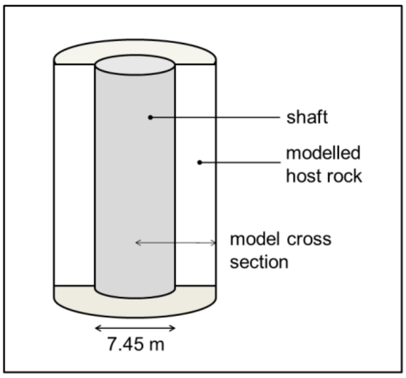

Figure 2-1 Schematic of the shaft-rock system. The rock comprises intact Georgian Bay Shale and an EDZ of depth 1.1 m. The seal is a 70:30 bentonite/sand mix.

Reactive transport models were developed to simulate the evolution of the interface between the bentonite / sand mixture and the Georgian Bay Shale. Radially symmetric 1-D models were constructed, with an outer radius of 10 m, at which distance it was assumed that the *in situ* groundwater was unaffected by interactions with the bentonite. The 1.1 m thick EDZ region was represented as a region of Georgian Bay Shale with increased porosity (14.2%) and enhanced effective diffusion (1.7×10^{-12} m^2/s) compared to the intact rock (7.1% and 8.6×10^{-13} m^2/s respectively). Simplified initial mineral assemblages that were specified in the modelling are shown in Table 2-1. The simulations were specified to run until 100 000 years.

Table 2-1 Simplified compositions of bentonite/sand mix and Georgian Bay Shale.

Bentonite / Sand	
Mineral	**Vol.%**
Montmorillonite(Na)	44.82
Quartz	1.53
Cristobalite	1.74
Calcite	0.50
Gypsum	0.59
Sand (quartz)	21.82
Porosity	29.00
TOTAL	**100.00**

Georgian Bay Shale	
Mineral	**Vol.%**
Calcite	8.93
Dolomite	9.76
Quartz	26.08
Chlorite	14.66
Illite	33.47
Porosity[1]	7.1
TOTAL	**100.00**

1. Note that in the reactive transport models an enhanced porosity is assumed in the host rock at the Excavation Damaged Zone, and initial mineral volumes are scaled accordingly.

Mineral dissolution/precipitation kinetics were fully coupled with porosity evolution. Diffusion of solutes was coupled to the evolving porosity using a linear Archie's Law ($D_{eff} = \theta D_{pore}$, where D_{eff} is the effective diffusion coefficient, θ is the porosity and D_{pore} is the porewater diffusion coefficient). The formulation allows the effective diffusion to tend to zero if porosity becomes completely clogged. For this reason, minimum grid cell sizes must be chosen to be representative of the thickness of clogging that would be expected to be needed in the real system in order to completely prevent diffusion of solutes. A thickness of 1 cm was chosen for the simulations.

Both rock and engineered materials were allowed to undergo alteration via dissolution/precipitation reactions. The salinity of the Georgian Bay Shale porewater is sufficiently high (ionic strength = 7.65 M) that it was necessary to use the Pitzer approach (Pitzer, 1991) to obtain more accurate activities of aqueous species than would be provided by standard Debye-Hückel models. Pitzer data from the Yucca Mountain Project 'YPF' database was used to model ion activities in the highly-saline groundwaters (USDOE, 2007). Thermodynamic data for the minerals species were taken from the database 'thermo.com.V8.R6+' (based on the EQ3/6 database generated by Lawrence Livermore National Laboratory, sometimes referred to as the 'LLNL' dataset).

Potential secondary minerals that could form in the system were identified after considering the available supporting experimental data and natural analogue data. Additionally, a supporting investigation of mineral stability was undertaken to determine the most stable clay minerals in the system Na_2O-MgO-Al_2O_3-SiO_2-H_2O using the 'thermo.com.V8.R6+' database. The activity diagrams produced suggest that if bentonite comes into contact with water compositions which have a relatively high $Mg^{2+}/(H^+)^2$ activity ratios, montmorillonite could undergo alteration to magnesium-rich clay minerals such as saponite (tri-octahedral smectite) (Figure 2-2), if kinetically feasible. Saponite is observed in weathered rocks and soil, especially those rich in ferromagnesian minerals and it can be found in lake and ocean sediments and hydrothermal systems (Wilson, 2013).

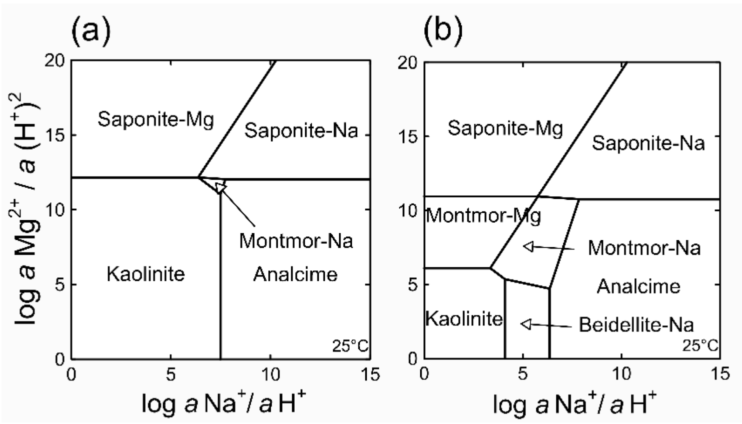

Figure 2-2 Activity diagrams for the system Na_2O-MgO-Al_2O_3-SiO_2-H_2O at T = 25 °C, P = 1 bar. Diagram (a) has dissolved silica activity set at quartz equilibrium; diagram (b) has it set at amorphous SiO_2 equilibrium. The diagram includes clay minerals and analcime as a representative sodium-rich framework silicate (albite, paragonite and pyrophyllite were suppressed).

The complete set of potential secondary minerals that were identified in the preliminary thermodynamic modelling are listed in Table 2-2. Illite was not included as a bentonite alteration product, as empirical models of smectite illitization show that it is likely to be negligible over the considered timescales under conditions of low temperature (< 100 °C) and near-neutral pH, even when relatively high concentrations of K^+ are present (e.g., Karnland and Birgersson, 2006; Quintessa, 2011). Given that the ambient temperature is expected to be low in the main part of DGR (~22 ºC) due to a lack of radiogenic heating (Quintessa, 2011), and shaft seals are at even shallower depths, and hence lower temperature, K-smectite minerals were included instead.

Table 2-2 Potential alteration products included in reactive transport simulations

Mineral	**Composition**
Bentonite Alteration Products	
Brucite	$Mg(OH)_2$
Saponite (Na, Mg, K, Ca)	$(Na_{0.33} / K_{0.33} / Ca_{0.165} / Mg_{0.165})\ Mg_3Si_{3.67}Al_{0.33}O_{10}(OH)_2$
Beidellite (Na, Mg, K. Ca)	$(Na_{0.33} / K_{0.33} / Ca_{0.165} / Mg_{0.165})\ Al_2Si_{3.67}Al_{0.33}O_{10}(OH)_2$
Montmorillonite (Mg, K, Ca, Na)	$(Na_{0.33} / K_{0.33} / Ca_{0.165} / Mg_{0.165})\ Al_{1.67}Mg_{0.33}Si_4O_{10}(OH)_2$
Kaolinite	$Al_2SiO_5(OH)_4$
Analcime	$Na_{0.96}Al_{0.96}Si_{2.04}O_6 \cdot H_2O$
Sepiolite	$Mg_4Si_6O_{15}(OH)_2 \cdot 6H_2O$
Palygorskite	$Mg_{2.84}Al_{1.8}Si_{7.73}O_{20}(OH)_2(OH_2)_4 \cdot 4H_2O$
Host Rock Alteration Products	
Analcime	$Na_{0.96}Al_{0.96}Si_{2.04}O_6 \cdot H_2O$
Kaolinite	$Al_2Si_2O_5(OH)_4$

Dissolution / precipitation reaction kinetics were represented using a Transition State Theory (TST) approach with the reaction rate depending on the acid, neutral, base and carbonate concentrations in the porewater:

$$\frac{dm}{dt} = A(m)\left(k_1 a_{H^+}^{n_1} + k_2 + k_3 a_{H^+}^{n_3} + k_4 f_{CO_2}^{n_4}\right)\left(\frac{Q}{K} - 1\right).$$

Here, m (mol) is the abundance of the mineral in question, $A(m)$ (m^2) is its reactive surface area (which depends upon its abundance), $k_{1,2,3,4}$ ($mol/m^2/s$) are the rate constants for acid, neutral, base and carbonate mechanisms respectively, and $n_{1,3,4}$ are dimensionless catalysis constants for acid, base and carbonate rates respectively. a_{H^+} is the activity of H^+, f_{CO_2} is the fugacity of CO_2 and Q and K are the ion activity product and equilibrium constant for the mineral.

The compilation of kinetic data by Palandri and Kharaka (2004) was used as the primary data compilation (k and n values) for silicate and carbonate minerals. Kinetic data for montmorillonite dissolution from Rozalén et al. (2008) was refitted to the form above and was used as a proxy for saponite, beidellite and palygorskite.

Measured values of dissolved silica concentrations are not available for the Georgian Bay Shale, so different assumptions regarding silica buffering were tested in the models (amorphous silica or quartz buffering was assumed). The models were implemented in Quintessa's QPAC software and the simulations explored the evolution of the bentonite/sand mixture over 100 000 years.

3. Results

Mineral volume fractions in the system at 100 000 y are shown in Figure 3-1 for the amorphous silica and quartz buffering assumptions for silica in the Georgian Bay Shale groundwater.

Over 100 000 years, minor alteration of the primary minerals at the shaft seal-rock interface occurred in the simulation assuming amorphous silica buffing in the Georgian Bay Shale (Figure 3-1, top). This results in an alteration zone in which porosity becomes clogged over a thickness of a few centimetres. The main alteration product in the bentonite/sand was saponite, whereas in the shale, it was analcime (which was included as a representative sodium-rich framework silicate). Partial ion exchange of the Na-montmorillonite to K-montmorillonite was seen across the bentonite.

Specifying quartz buffering in the Georgian Bay Shale leads to greater amounts of alteration. By 100,000 years, primary montmorillonite had been replaced completely by K-saponite and kaolinite in the bentonite/sand near the shale to a depth of around 2 cm. Porosity was reduced in this region to 3%, but was not completely clogged (unlike the amorphous silica buffering case). The overall difference in the pattern of silicate mineral evolution in the shale is due to the lower dissolved silica activity in the shale porewater which leads to the stabilisation of kaolinite rather than analcime.

The findings in all variant cases that were considered in the study was that alteration of the primary phases is restricted to a narrow (<5 cm) band around the shaft seal-rock interface.

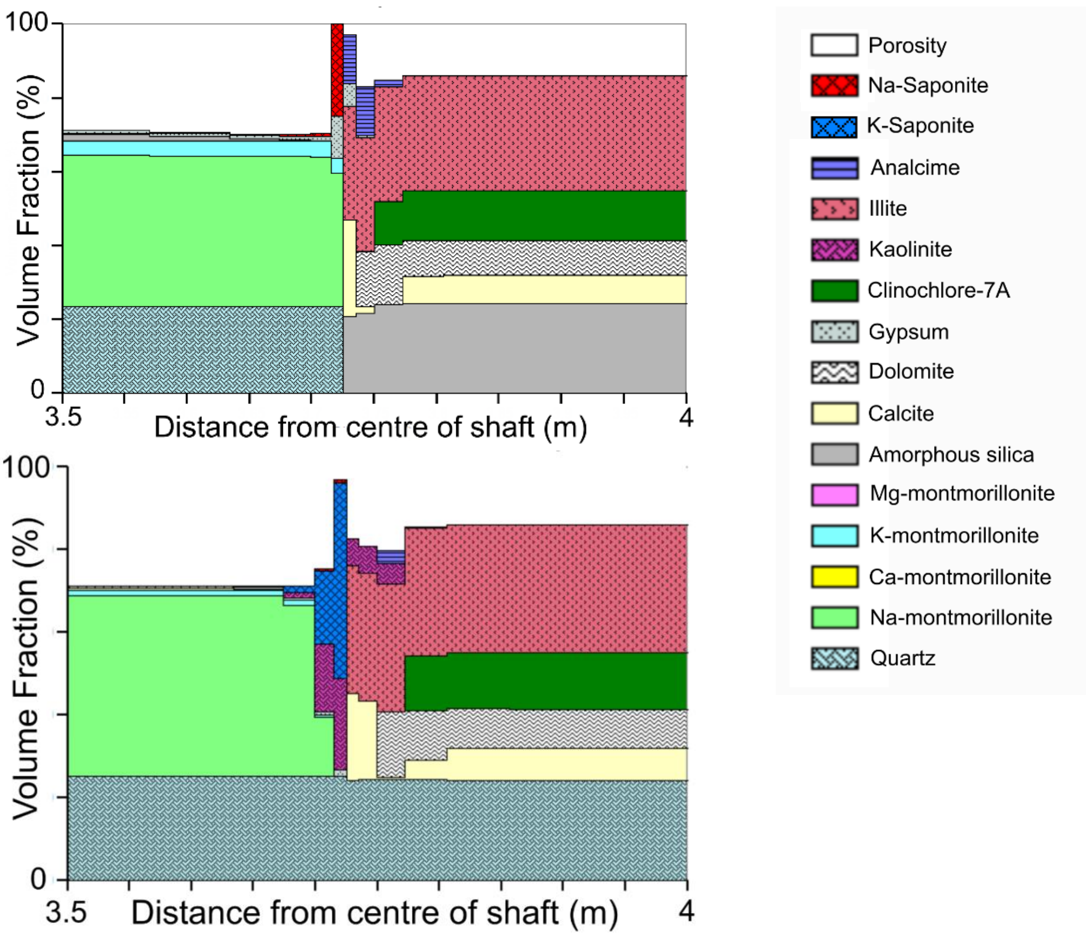

Figure 3-1 Volume fraction plots for bentonite/sand – shale interface at 100 000 years assuming amorphous silica-buffering (top) and quartz buffering (bottom) in the Georgian Bay Shale. The coordinates on the x axes refer to the distance from the centre of the shaft.

4. Conclusions

None of the simulations predicted a significant increase in bentonite-sand porosity over 100,000 years and most of the thickness of the bentonite/sand shaft seal remained unaltered. Hence the models suggest that the performance of the bentonite/sand shaft seals in contact with hypersaline porewater should not be detrimentally affected. With regard to implications for shaft seal performance in the DGR, there was no significant increase in bentonite/sand porosity and the predicted alteration of primary montmorillonite (although more extensive than in the base case) is confined to the volume near to the interface with the shale, most of the bentonite/sand remaining unaltered (apart from partial replacement of Na-montmorillonite by K-montmorillonite).

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Laboratory and Numerical Investigation of the Hydro-mechanical Behaviour of the Cobourg Limestone

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The excavation of galleries and shafts of a deep geological repository (DGR) can induce damage in the surrounding rock. The excavation damage zone (EDZ) has higher permeability and reduced strength compared to the undisturbed rock and those factors must be considered in the safety assessment of the DGR. Ontario Power Generation is currently proposing a DGR for the management of its low and intermediate level nuclear wastes in a sedimentary rock formation of the Michigan Basin, known as the Cobourg limestone. The authors are conducting experimental and theoretical research in order to confirm the hydro-mechanical behaviour of the host rock, both in the undamaged and damaged state. The experimental program consisted of triaxial tests with a controlled loading rate up to and beyond failure. During the tests, the permeability and the seismic wave velocity were measured for six specimens cored parallel and perpendicular to the bedding plane. The experimental results show that the Cobourg limestone is an anisotropic material with respect to the mechanical behaviour. However, the measured permeability of the intact Cobourg limestone does not show significant difference for the six specimens. The permeability measured post failure is 2~3 orders of magnitude higher than that of the intact rock. The evolution of the compressional and shear-wave velocities and shear wave splitting as a function of the axial stress confirms the anisotropic behaviour of the Cobourg limestone. An anisotropic elasto-plastic model based on the microstructure tensor approach was developed to simulate the tests. The preliminary simulations successfully re-produced the experimental results.

1. Introduction

Argillaceous rocks are candidate host and/or cap formations for the geological disposal of nuclear wastes in many countries. The understanding of the long-term hydro-mechanical behaviour of such rocks is one of the essential requirements for the assessment of their performance as a barrier against radionuclide migration. The extent and the hydro-mechanical evolution of an excavation damage zone are important aspects to be assessed for the design of plugs and seals of the repository, if deemed necessary. In Canada, the Cobourg limestone is selected as the host rock for a deep geological repository for the management of low and intermediate level nuclear wastes proposed by Ontario Power Generation. In order to understand the hydro-mechanical behaviour of the Cobourg limestone, the Canadian Nuclear Safety Commission (CNSC) collaborated with the University of Toronto to perform experimental investigations of its hydro-mechanical behaviour with a special attention to the evolution of hydraulic property with mechanical damage induced by the excavation of the repository. Using the data from the triaxial tests, we developed constitutive relationships for the hydro-mechanical behaviour of the Cobourg limestone and simulated the evolution of permeability with the mechanical damage of the rock.

2. Description of samples and testing equipment

The Cobourg limestone is a mottled light to dark grey, very fine- to coarse-grained, very hard, fossiliferous argillaceous limestone (NWMO 2011). The block samples for the experiment were collected at the St. Mary's quarry near the Darlington nuclear power plant. The cylindrical testing specimens were cored parallel and perpendicular to the bedding plane in the laboratory. Porosity and density of the limestone were measured according to the ISRM standard procedure (1981a) and are shown in Table 2-1.

Table 2-1 Physical properties of the Cobourg limestone measured at the RFDF

Specimen number	Length (cm)	Diameter (cm)	Porosity (%)	Dry density (g/cm^3)	Density at saturation (g/cm^3)
CLV-1-T	12.50	5.04	0.82	2.33	2.34
CLV-3-T	12.50	5.04	1.26	2.31	2.32
CLV-4-U	12.50	5.04	0.83	2.32	2.33
CLH-1-T	12.50	5.04	0.85	2.33	2.34
CLH-1-U	12.50	5.04	0.74	2.33	2.34
CLH-2-T	12.50	5.04	0.95	2.33	2.34
CLH-2-U	12.50	5.04	0.90	2.32	2.33
CLH-3-T	12.50	5.04	0.93	2.32	2.33
CLH-3-U	12.50	5.04	1.09	2.32	2.33

CLV: specimens prepared perpendicular to the bedding plane, CLH: specimens prepared parallel to the bedding plane.

The triaxial tests were performed in the geophysical imaging cell (GIC) at the Rock Fracture Dynamics Facility (RFDF) at the University of Toronto. The cell is equipped with ultrasonic-wave velocity stacks oriented along three orthogonal axes of X, Y and Z, enabling us to measure the evolution of compressional and shear wave velocities as a function of differential stresses. During the experiments, in addition to the axial deformational measuring unit of the Mechanical Testing Systems (MTS), two separate LVDTs close to the specimen outside the cell (integrated part of the GIC) were also used to measure axial deformation of the specimen. The diametral strain of the specimen was measured with an in-built cantilever system within the GIC.

The axial loading rate was controlled at a strain rate of 1.6×10^{-6}. The permeability of the specimens was measured with the pulse decay method (Brace et al. 1968). The servo-controlled load was kept on hold during the permeability measurement. A servo-control Quizix pump system (two pumps under independent constant control mode) was used to regulate the top and bottom pore pressures and to generate hydraulic pulses for permeability measurements under targeted axial stress levels up to the post failure region. Prior to the permeability measurement, the upstream and downstream storage factors of the testing cell were evaluated using a steel sample of same size as that of the rock specimens following methods outlined by Boulin et al. 2012.

3. Experimental results

Six tests were conducted on specimens parallel (3 samples) and perpendicular (3 samples) to the bedding plane under hydrostatic and differential stress conditions with a confining pressure of 5 MPa and an initial pore pressure of 3 MPa. The permeability of each specimen was measured at the initial hydrostatic and later differential stresses. Once a target differential stress was reached, a 1 MPa hydraulic pulse was applied to measure the permeability of the specimen. Figure 3-1 shows the representative stress-strain relationship of specimen CLH-1-U (cored parallel to the bedding plane) and the evolution of permeability with axial strain. Figure 3-2 shows the failure mode of specimen CLH-1-U and its 3D sketch corresponding to the seismic velocity measurement. Figure 3-3 shows the compressional wave velocities along three orthogonal axes and the permeability values measured at different axial stresses for specimen CLH-1-U. Figure 3-4 shows the representative stress-strain relationship of specimen CLV-3-T (cored perpendicular to the bedding plane) and the evolution of permeability with axial strain. Figure 3-5 shows the failure mode of specimen CLV-3-T and its 3D sketch corresponding to the seismic velocity measurement. Figure 3-6 shows the compressional wave velocities along three orthogonal axes and the permeability values measured at different axial stresses for specimen CLV-3-T.

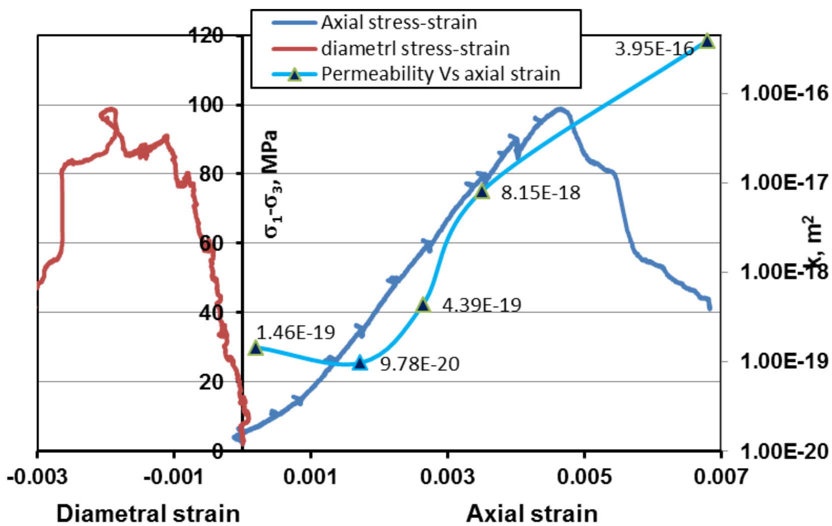

Figure 3-1. The stress-strain relationship of specimen CLH-1-U and the evolution of permeability with axial strain.

Figure 3-2. Failure mode of specimen CLH-1-U (left image shows intact specimen) and the 3D sketch corresponding to the seismic velocity measurement.

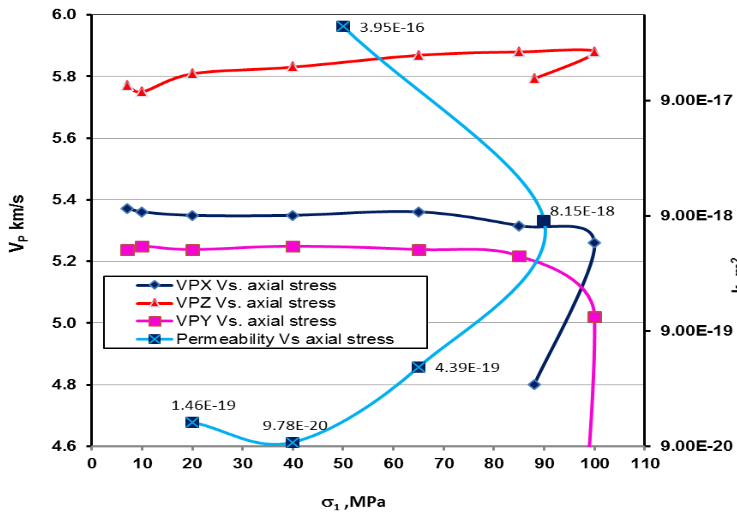

Figure 3-3. Compressional wave velocities along three orthogonal axes and the permeability values measured at different axial stresses for specimen CLH-1-U.

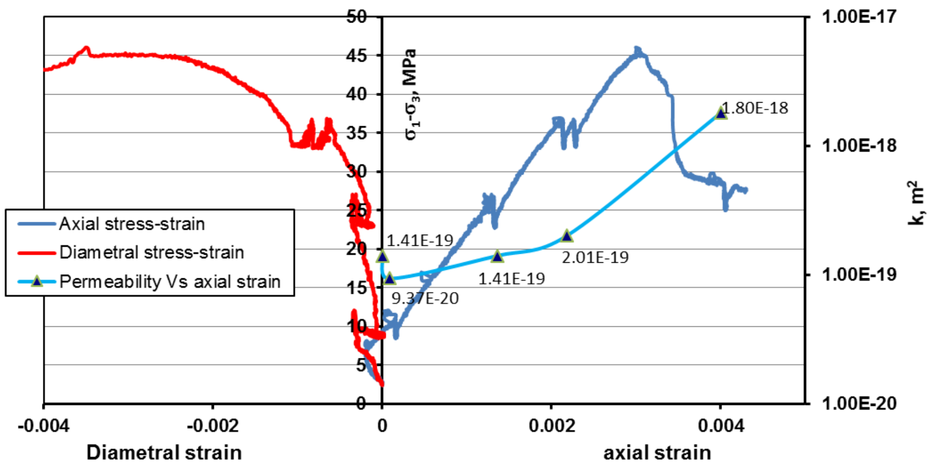

Figure 3-4. The stress-strain relationship of specimen CLV-3-T and the evolution of permeability with axial strain.

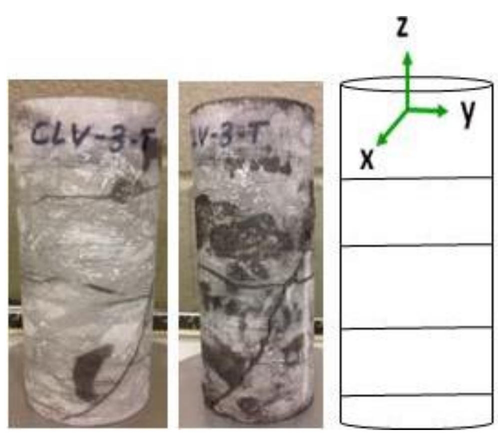

Figure 3-5. Failure mode of specimen CLV-3-T and the 3D sketch corresponding to the seismic velocity measurement.

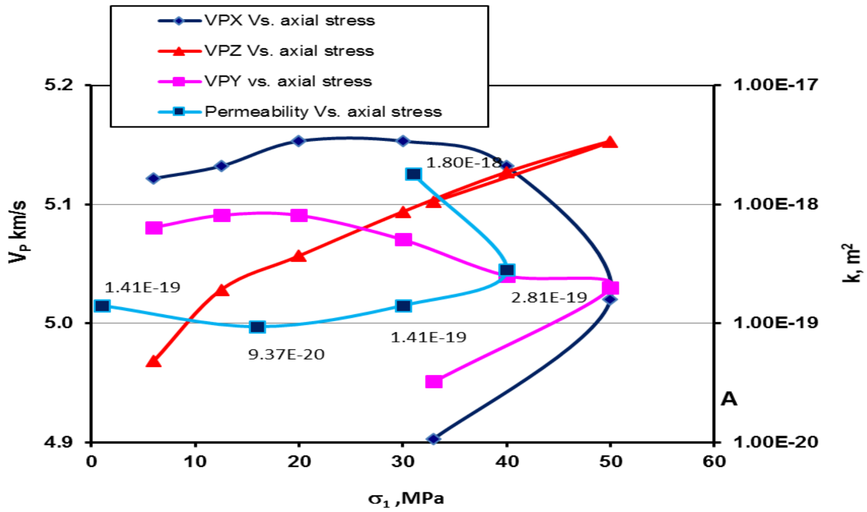

Figure 3-6. Compressional wave velocities along three orthogonal axes and the permeability values measured at different axial stresses for specimen CLV-3-T.

4. Numerical simulations of triaxial test results

The experimental results of triaxial tests were used for numerical investigation of the coupled hydro-mechanical behaviour of the Cobourg limestone. The constitutive relationship was developed to describe the stress-strain behaviour of the limestone. The constitutive relationship relates the stress increment to the strain increment

$$d\boldsymbol{\sigma} = \mathbf{D}(d\boldsymbol{\varepsilon} - d\boldsymbol{\varepsilon}^p)$$

where $d\boldsymbol{\sigma}$ is the increment of the stress tensor (written as a vector); $d\boldsymbol{\varepsilon}$ is the increment of total strain tensor (written as a vector); $d\boldsymbol{\varepsilon}^p$ is the increment of the plastic strain tensor (written as a vector); and $\mathbf{D}$ is the elastic stiffness tensor (written as a matrix).

The elastic stiffness tensor is transversely isotropic, with two principal directions, one parallel and one perpendicular to the bedding plane. Furthermore, the degradation of the Young's moduli with accumulated irreversible strain is taken into account.

The plastic strain, that is assumed to be a measure of damage, is obtained using a Mohr-Coulomb criterion, where the cohesion c and the friction angle ϕ are made directionally-dependent using the microstructure tensor approach (Pietruszczak and Mroz 2001). Strain hardening and post failure softening are taken into account by making those parameters vary with the effective plastic strain. Figure 4-1 shows the modelled stress-strain curves for the Cobourg limestone at two loading orientations for specimens CLV-3-T (perpendicular to the bedding plane) and CLH-1-U (parallel to the bedding plane). In order to understand the effect of the mechanical damage on the evolution of permeability, the computed plastic strain (x-axis) is plotted against the measured permeability (y-axis) under the defined loading conditions. Figure 4-2 shows the evolution of permeability with the computed plastic strain for both specimens CLH-1-U (β=90°) and CLV-3-T (β=0°), where β is the angle between the bedding plane and the horizontal axis X.

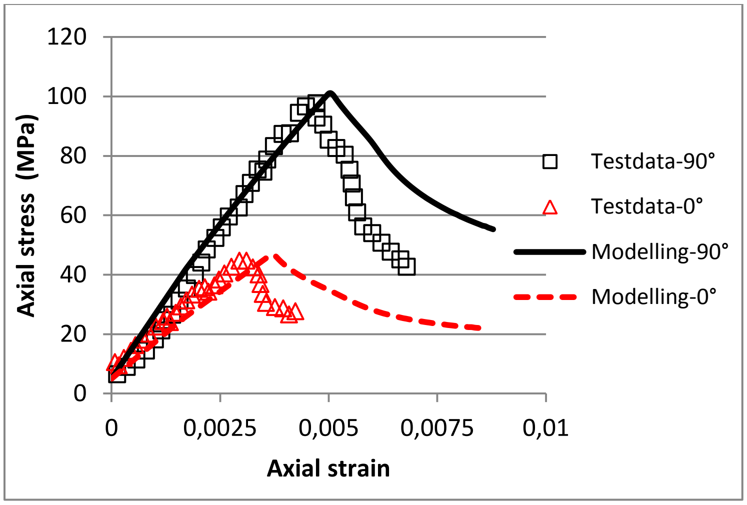

Figure 4-1. Experimental and modelling results on stress-strain relationship for specimens CLH-1-U (β=90°) and CLV-3-T (β=0°).

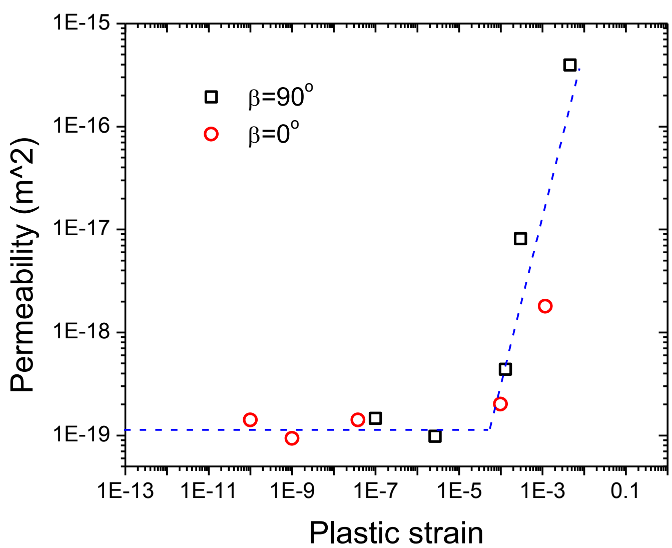

Figure 4-2. Evolution of permeability with the computed plastic strain for specimens CLH-1-U (β=90°) and CLV-3-T (β=0°).

5. Conclusion

The Cobourg limestone is an anisotropic material, and its strength and deformation behaviour are direction dependent. However, the permeability of the intact limestone does not show significant difference for rock specimens cored at two different orientations (i.e. parallel and perpendicular to the bedding plane). These permeability values measured with the transient method (i.e. pulse decay method) are comparable to the results measured with the conventional method (Selvadurai and Jenner 2012). The permeability measured post-failure is 2~3 orders of magnitude higher than that of intact rock. This means that the permeability of the highly damaged limestone due to excavation could be at least 3 orders of magnitude higher than that of the undamaged rock. The enhanced permeability of the damaged rock must be considered in the safety assessment of the repository, and should be mitigated with sealing systems if needed. Using data from the experiment, a microstructure tensor-based, anisotropic, elastoplastic hardening-softening model was developed for the Cobourg limestone. The model is able to reproduce the inherent anisotropy due to bedding and the evolution of permeability with damage for both specimens CLH-1-U and CLV-3-T.

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13. **PROGRAMME OF DOPAS 2016 SITE VISIT TO OLKILUOTO**

Friday 27 May 2016: Visit schedule:

07.15	Departure from the hotel by bus
08.45	Arrival at Olkiluoto Visitor Centre
	Coffee and check-in (passport needed)
09.15	Presentations in the auditorium
	Olkiluoto presentation
	POPLU presentations (Posiva Oy)
10.45	Lunch buffet
11.30	Area tour
	Visit to final underground LILV repository
	Olkiluoto site tour by bus including Olkiluoto 3 construction site
13.30	Transfer back to the Visitor Centre
	Coffee
13.45	Visit ends, departure to Turku
15.30	Arrival to Turku Airport
16.00	Arrival to Turku railway station / Radisson Blu Marina Palace

The third day of the seminar was reserved for the Olkiluoto Site Visit and this opportunity was utilised by 46 DOPAS 2016 participants. The site visit programme was provided to the preregistered visitors at the time of DOPAS 2016 confirmation letters. The visit consisted of two parts: (1) Session on visitor centre auditorium and (2) site tour.

The programme was in English but the participants from Russian waste management company NO RAO had simultaneous interpretation, while the materials presented were not available for pre-visit consideration.

Four presentations were given in visitor centre:

- Olkiluoto site introduction by Anne Niemi, TVO
- Posiva status and plans for spent fuel waste management by Johanna Hansen, Posiva Oy
- DOPAS Experiment 4 POPLU Experiment by Petri Koho, Posiva Oy
- Rock suitability classification for POPLU by Paula Kosunen, Posiva Oy

The afternoon of day 3 was reserved for the area tour and it was arranged in two parts due the size of the group and the tour was hosted by Kimmo Kemppainen, Posiva Oy, Johanna Hansen Posiva Oy, Anne Niemi, TVO, and Kanerva Kuisma, TVO. The first part of the visit was a bus tour. The visitors did visit the ONKALO construction site (surface-only) and received information on the underground working conditions. This was followed by an Olkiluoto 3 (OL3) construction site visit. OL3 includes as a part of this major scientific-technical project extensive use of reinforced concrete construction for its safety classified components and in that way it has several similarities with implementation of POPLU plug.

The site tour included an underground repository visit to the LILW operating waste facility and to the adjacent ONKALO Exhibition at the depth of 60 meters below surface located in the Olkiluoto host rock. The EBS components and the research topics for final disposal were presented in the ONKALO Exhibition (see Figure 13-1.)

Figure 13-1. ONKALO Exhibition in VLJ repository

14. SUMMARY OF THE DOPAS 2016 ARRANGEMENTS

The DOPAS 2016 seminar was arranged by a programme committee and planning team consisting of the following persons.

- Johanna Hansen, Posiva, Chair
- Marjatta Palmu, Posiva
- Matt White, GSL
- Mary Westermark, SKB, Secretary
- Jean-Michel Bosgiraud, Andra
- Marie Garcia, Andra
- Jiri Svoboda, CTU
- Markéta Dvoráková, SURAO (Irena Hanusová during the maternity leave)
- Dean Gentles, RWM
- Erika Holt, VTT
- Christophe Davies, EC

The DOPAS 2016 seminar planning team was responsible for the organization of the DOPAS 2016 scientific programme, site visit arrangements and selection of independent rapporteur and nominating Chair and co-chair persons for seminar. The advertisement of DOPAS 2016 seminar and publishing the Call for Abstracts and other related material were also arranged by this team.

The first seminar planning group meeting took place in February 2015 in Rauma, Finland in conjunction of DOPAS WP2 meeting. At that time the organizational framework for the seminar was established and the event venue and dates were fixed. The next organizing meeting was held in conjunction with the DOPAS Management team meeting in Stockholm/Oskarshamn June 2015 and the Call for abstracts was published after that meeting. The third meeting was a call-in meeting in January 2016 at which time the programme of the seminar was finalized. The last meeting was in Wettingen, Switzerland in conjunction with the DOPAS Management Team meeting in April 2016, at which the final adjustments and panel discussion topics were decided by the WP leaders and Experiment leaders at the meeting.

The practical DOPAS 2016 arrangements were taken care by Posiva and support services were purchased from TVO (majority owner of the Posiva). SKB supported the Seminar by compiling and uploading the presentations at the seminar to the seminar website. The DOPAS 2016 seminar public web pages were available under http://www.posiva.fi/en/dopas pages and the registrations to the seminar were arranged via web site

The DOPAS 2016 seminar’s physical arrangements were arranged in Radisson Blu Marina Palace at Turku, Finland and the meeting buffet dinner was held at the Forum Marinum's Restaurant Daphne.

To facilitate attendee questions and presenter responses during the the course of the seminar special tool was used: The seminar participants could post questions online to the virtual message wall during the seminar. The questions were compiled, presented and replied at the end of the day 2. The method was quite a novel for this type of venue and subject and so there was no prior experiences on how best to use this tool, and this limited the amount of questions by the audience. However, the method was effective enough that it should be considered for use in future technical/scientific events as its allows for audience interaction during the presentations and would be particularly useful if a means were available for each presenter to see the questions related to them at the time of their presentation questions.

The DOPAS 2016 Seminar in addition to providing an excellent concluding venue for the DOPAS Project, fulfilled the dissemination needs of this project by involving participants from 50 different organisations and 16 countries. The meeting presentations were made available on the internet during the seminar and the facilitators and chairs ensured that there was plenty of opportunity for discussions and information exchange during the three seminar days. The feedback in the end of the seminar were very laudatory.