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.

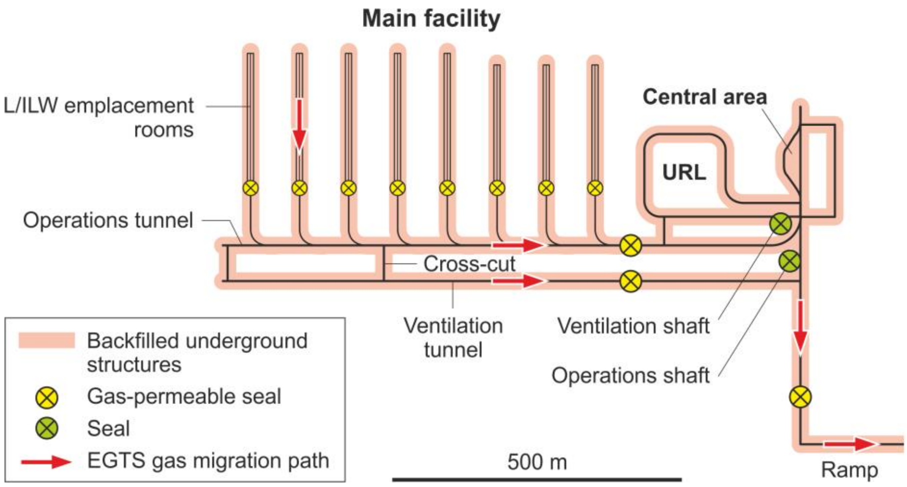

Figure 1-1. Nagra's generic concept for an L/ILW repository, planned backfilling and position of seals. EGTS gas migration path is shown by red arrows. (after Poller, 2014).

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.

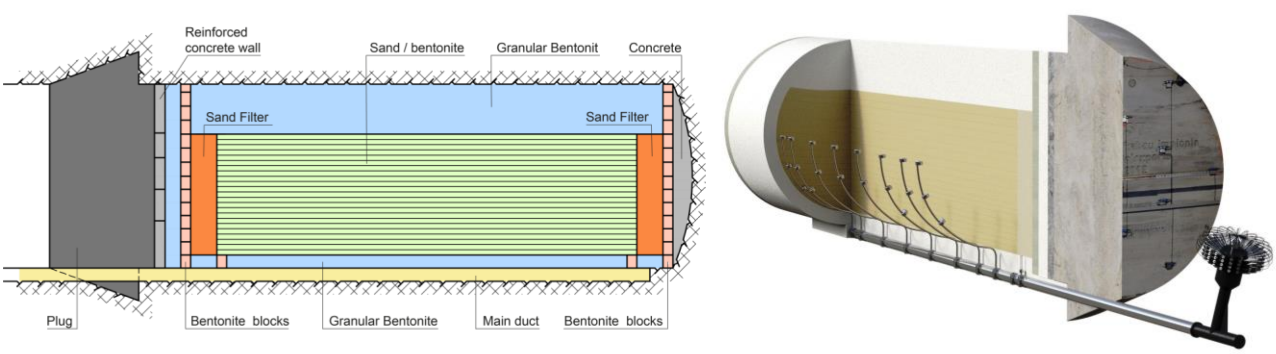

Figure 3-1. Conceptual experimental layout (left) and cut-away visualization (right) showing sand/bentonite and granular bentonite bodies with instrument risers and main duct below the tunnel.

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	●
Port lines	PL	10	■
Total pressure cells	TPW/TPB	23	○
Volumetric water content	TDP/TDL	38	● / ▬
Seismic sensor	SE	34	●
Psychrometers	PS	30	▲
Relative humidity	RH	20	▲
Temperature	PT1000	3	
Displacement	DI	4	

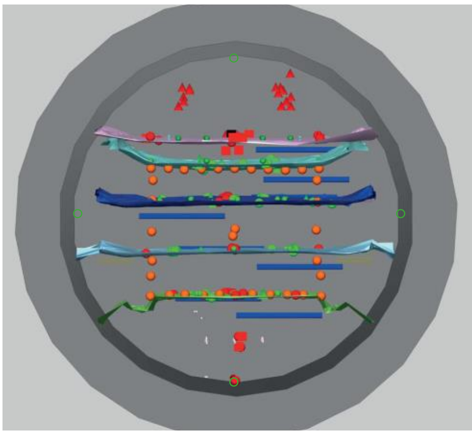

Figure 3-2. List of installed sensors, abbreviations, quantity and symbol (left). Cross-section (right) shows position of the sensors and surfaces of instrumentation layers 40-50 cm apart.

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).

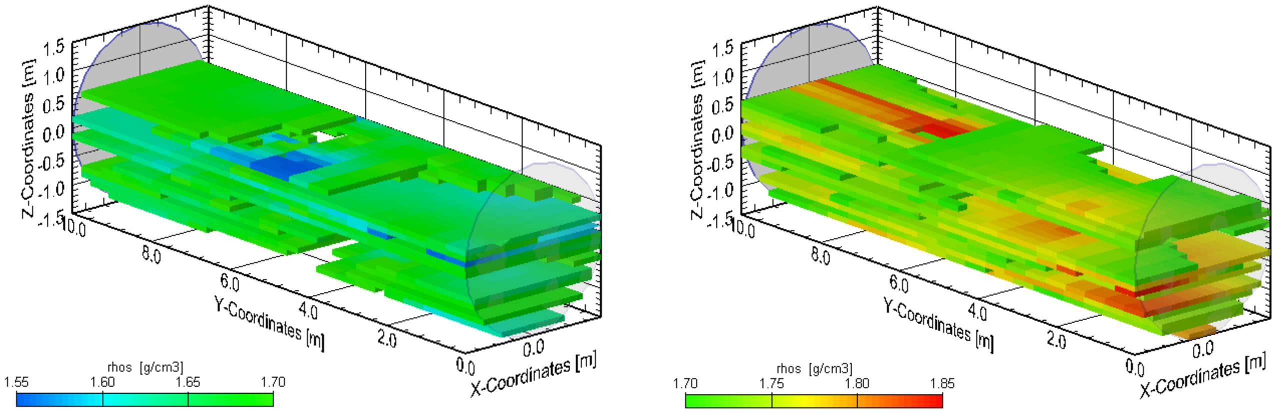

Figure 3-3. Distribution of S/B dry densities smaller (left) and larger (right) than 1.7 Mg/m^3.

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

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6 References

Dixon, D., Chandler, N., Graham, J. & Gray, M. N. N. (2002): Two large-scale sealing tests conducted at Atomic Energy of Canada's underground research laboratory: the buffer-container experiment and the isothermal test. Canadian Geotechnical Journal, 39(3), 503–518. doi:10.1139/T02-012.

JAEA (1999): H12: Project to establish the scientific and technical basis for HLW disposal in Japan ("H12 report" in short). Japan Atomic Energy Agency.

Manca D. (2015): Hydro-chemo-mechanical characterisation of sand/bentonite mixtures, with a focus on the water and gas transport properties, Thèse No. 6790. École polytechnique fédérale de Lausanne EPFL, Lausanne, 2015.

Mata Mena, C. (2003). Hydraulic behaviour of bentonite based mixtures in engineered barriers: The Backfill and Plug Test at the Äspö HRL (Sweden). Doctoral Thesis Universitat Polytecnica Catalunya, Barcelona.

Nagra (2008): Effects of post-disposal gas generation in a repository for low- and intermediate-level waste sited in the Opalinus Clay of Northern Switzerland. Nagra Technical Report NTB 08-07. Nagra, Wettingen.

Nagra (2014a): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage Sicherheitstechnischer Bericht zu SGT Etappe 2 Sicherheitstechnischer Vergleich und Vorschlag der in Etappe 3 weiter zu untersuchenden geologischen Standortgebiete. Nagra Technical Report NTB 14-01. Nagra, Wettingen.

Nagra (2014b): Sensitivity analyses of gas release from a L/ILW repository in the Opalinus Clay in the candidate siting regions of Northern Switzerland. Nagra Arbeitsbericht NAB 13-92. Nagra, Wettingen.

Poller, A., Smith, P., Mayer, G. & Hayek, M. (2014): Modelling of Radionuclide Transport along the Underground Access Structures of Deep Geological Repositories. Nagra Technical Report NTB 14-10. Nagra, Wettingen.

Senger, R., Lanyon, G.W., Marschall, P., Vomvoris, S. & Fujiwara, A. (2006). TOUGH2/iTOUGH2 analysis of the gas migration test (GMT) at the Grimsel Test Site (Switzerland). Proceedings, TOUGH Symposium 2006, Lawrence Berkeley National Laboratory, Berkeley, California, May 15–17, 2006.

Tashiro S., Fujiwara A. and Senoo M. (1998): Study of the permeability of engineered barriers for the enhancement of radioactive waste repository system. Nuclear Technology 121, p. 13-23.

Teodori, S.P., Rüedi, J., Reihnhold, M. & Manca, D. (2013): Design, testing and emplacement of sand-bentonite for the construction of a gas-permeable seal test (GAST). Proceedings of the ASME 2013 15th International Conference on Environmental Remediation and Radioactive Waste Management ICEM2013, September 8-12, 2013, Brussels, Belgium.