Oral Session 2B

Gas transfer

Chair: Paul Marschall - Frédéric Plas

GAS THRESHOLD PRESSURE TEST PERFORMED AT THE MT TERRI ROCK LABORATORY: EXPERIMENTAL DATA AND ANALYSIS

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ABSTRACT

Safety assessment of potential gas release from radioactive waste repositories in argillaceous formations requires information on gas transport properties of the host rock formation. In order to investigate gas transport in the Opalinus Clay, a multitude of borehole tests were performed at the Mont Terri Rock Laboratory. This paper presents the results of a comprehensive test campaign in borehole BGP4 (Figure 1), comprising a "classical" hydrotest with water injection and pressure recovery sequences and an extended gas threshold pressure test (Marschall et al., 2003). Finally, a detailed interpretation of both the hydraulic and gas test phase was conducted, using numerical single-phase and two-phase welltest simulators for data analysis. The joint interpretation provides a consistent set of single-phase hydraulic parameters and two-phase flow parameters with well-defined uncertainty ranges.

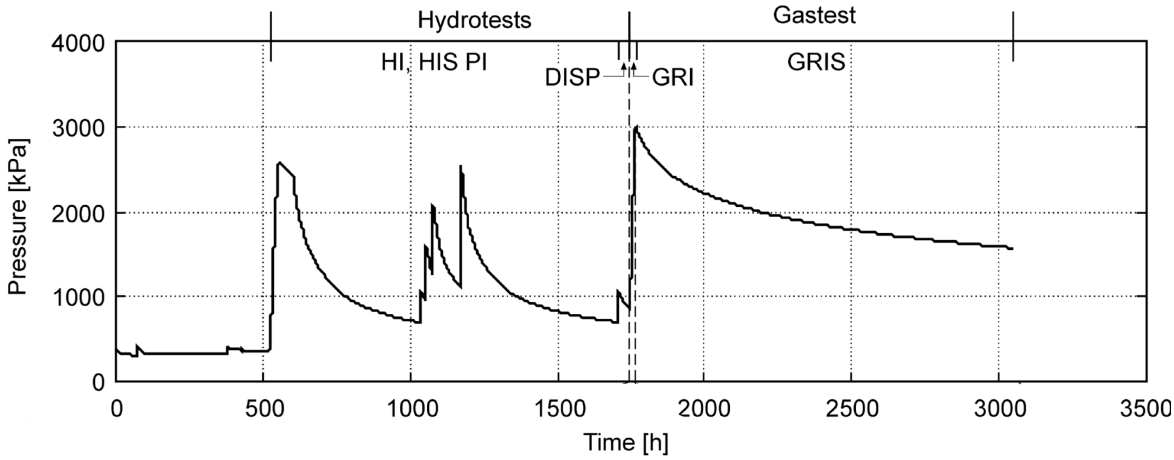

Figure 1: Sequence of hydraulic tests and gas threshold pressure tests in borehole BGP4 of the Mont Terri Rock Laboratory

In a first step, the hydrotest sequence performed in the borehole BGP4 between January and June 1997 was analysed with an inverse parameter estimation approach and a subsequent uncertainty analysis. The flow model used for the analysis was a radial homogeneous formation of infinite lateral extent with a constant wellbore storage. Darcy flow was assumed. The fitting parameters were the hydraulic conductivity, specific storage, static formation pressure and wellbore storage. Uncertainties in these fitting parameters due to uncertainties in the non-fitting parameters (flow rates and borehole radius) were estimated. In the analysis, no evidence for other non-hydraulic processes (e.g. borehole closure due to creep) was found. Furthermore, a radial composite finite skin model was adopted to assess model uncertainty; however, this model did not significantly improve the overall match of the data.

The Gas Threshold Pressure Test (GTPT) in BGP4 was analysed in two stages. In 1999, an inverse parameter estimation approach was used, combined with a subsequent uncertainty analysis based on the flow model used in the previous hydrotest analysis (Croisé et al., 1999). In 2004 a refined interpretation was initiated which made use of complementary information on the two-phase flow behaviour of the Opalinus Clay, derived from laboratory experiments on drillcore specimens.

In the first GTPT interpretation stage, the fitting parameters were the intrinsic permeability, the formation compressibility, the wellbore storage, the gas entry pressure and the porosity. The two-phase flow constitutive relationships (capillary pressure-saturation and relative permeability-saturation relationships) were based on the Van Genuchten/Mualem and Grant approaches. In comparison to the hydrotests, the equivalent hydraulic diffusivity was about 30 times higher, with a permeability about 3 times higher and the specific storage 10 times lower than those deduced from the hydrotest analysis. The specific storage estimate corresponds well with compressibility values determined on rock samples in the laboratory. The estimate from the inverse simulation for the gas entry pressure corresponds very well with the estimate from the diagnostic analysis (~1MPa). According to the conceptual model (homogeneous medium, no gravity segregation, no fingering due to fluid viscosity differences or heterogeneities, gas movement dominated by capillary resistance, i.e. threshold pressure), the gas only penetrated 3-5 cm into the formation during the GTPT.

The second interpretation stage made use of additional test analyses from the enlarged data base of the Mont Terri project (in particular, new experimental data obtained within the framework of the ventilation and heater experiments conducted between 2000 and present). Further two-phase flow relationships were investigated and a set of two-phase flow parameters and their uncertainties is proposed. The constraining power of the new data led to a significant improvement of consistency between single-phase hydraulic parameters and two-phase flow parameters.

References:

Marschall, P., Croisé, J., Schlickenrieder, L., Boisson, J.Y., Vogel, P. & Yamamoto, S. (2003): Synthesis of hydrogeological investigations at the Mont Terri Site (Phases I to V): Mont Terri Technical Report 2001-02.

Croisé, J., Gilby, D., Lavanchy, J.M. & Senger, R.K. (1999): “GP Experiment: Analysis of the BGP-4 GRI & GRIS gas threshold pressure”, J. Croisé, , Mont Terri TN 98-25

GAS MIGRATION IN KBS-3 BUFFER BENTONITE: SENSITIVITY OF TEST PARAMETERS TO EXPERIMENTAL BOUNDARY CONDITIONS

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In the current Swedish repository design concept, hydrogen gas can be generated inside a waste canister by anaerobic corrosion of the ferrous metal liner. If the gas generation rate exceeds the diffusion rate of gas molecules in the buffer porewater, then gas will accumulate in the void-space of a canister until its pressure becomes large enough for it to enter the bentonite as a discrete gaseous phase.

Three long term gas injection tests have been performed on cylinders of pre-compacted Mx80 bentonite. Two of these tests were undertaken using a custom-designed constant volume and radial flow (CVRF) apparatus. Gas was injected at a centrally-located porous filter installed in the clay before hydration. Arrangements were made for gas to flow to three independently monitored sink-filter arrays mounted around the specimen. Axial and radial total stresses and internal porewater pressures were continuously monitored. The third test was performed using an apparatus which radially constrains the specimen during gas flow.

Under constant volume test conditions, breakthrough and peak gas pressures can significantly exceed the sum of porewater pressure and swelling pressure. Observed sensitivity of the breakthrough and peak gas pressures to the test boundary conditions suggests that gas entry is accompanied by dilation of the bentonite fabric. The experimental evidence provides conclusive evidence that gas moves through a system of highly unstable pressure-induced pathways. Gas entry and breakthrough under constant volume boundary conditions causes both the total stress and the porewater pressure to increase. It is possible to determine the point at which gas enters the clay by monitoring changes in these parameters. Abrupt drops in gas injection pressure, accompanied by similar increases in total stress, can be interpreted as pathway propagation events. The first pathways which form in the clay may not intersect the gas sinks. Additional gas pressure is often required to produce fully-conductive features which connect with the sinks.

The experimental evidence is consistent with the flow of gas along a relatively small number of crack-like pathway which propagate through the clay as gas pressure increases. This localisation of gas flow within pathways results in non-uniform discharge rates at the sinks. Some displacement of porewater by internal consolidation of the clay occurs at high gas pressures.

When gas injection stops, the gas pressure in the clay drops rapidly and then continues to fall slowly with time. The pressure transient approaches an asymptote which coincides with the zero flow rate condition. The gas pressure at the asymptote (shut-in pressure) represents the minimum pressure at which gas is mobile in the clay. The transient provides clear evidence of discrete gas pathway sealing events. During a shut-in, the gas pressure exceeds the internal porewater pressure by an amount equal to the capillary pressure. The decline in gas pressure during a post-peak transient reflects a similar decline in the porewater pressure. Gas flow ceases when excess gas pressure (i.e. relative to porewater pressure) falls below capillary pressure. In constant volume tests, the capillary pressure for bentonite is shown to be approximately equal to the swelling pressure. There is no evidence from these long-term tests that the development of gas pathways in any way compromises the sealing capacity of the bentonite barrier. The laboratory study clearly demonstrates the sensitivity of the gas migration process to experimental boundary conditions.

INFLUENCE OF TRAPPED AIR ON THE WATER SATURATION PROCESS IN A BACKFILLED KBS-3 TUNNEL - NUMERICAL CALCULATIONS

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One part of the development work for SKB's design of a deep repository for high-level radioactive wastes in crystalline rock consists of numerical modelling of the backfill saturation process and the hydraulic interaction between rock and the backfill. Within this work, the effects of air being trapped in the backfill material on the saturation process were considered. Examples of questions that were raised are: How will air, initially present in the backfill material and with no escape routes other than through the host rock, influence the backfill saturation process? What impact does the host rock hydraulic properties have on the air pressure build up inside the backfill? How important for the saturation process is the amount of dissolved gas in the host rock pore water?

The influence of trapped air in the backfill on the water saturation process was studied with Code_Bright version 2.2, which is a finite element code for thermo-hydro-mechanical analyses of geological media. Code_Bright handles standard two-phase flow of gas and liquid in porous materials. The two-phase flow model considers advective transport of gas in the unsaturated state, diffusion of dissolved gas in the saturated state and dissolution of gas into the liquid phase.

A number of 1D, axially symmetric isothermal models were analyzed. The models included a backfilled tunnel and a portion of host rock (Figure 1). The backfill was assumed to be a mixture of 30 % bentonite and 70 % crushed rock compacted to an average degree of compaction of 90 % modified Proctor. At the model's outer boundary, water and gas pressure boundary conditions were set and the water supply to the backfill was varied by varying the rock permeability. The rock was kept saturated. Thus, the air present in the initially unsaturated backfill had to escape by diffusion through the rock. For reference, models assuming unlimited escape of air, i.e. with a constant atmospheric gas pressure inside the backfill, were also analyzed.

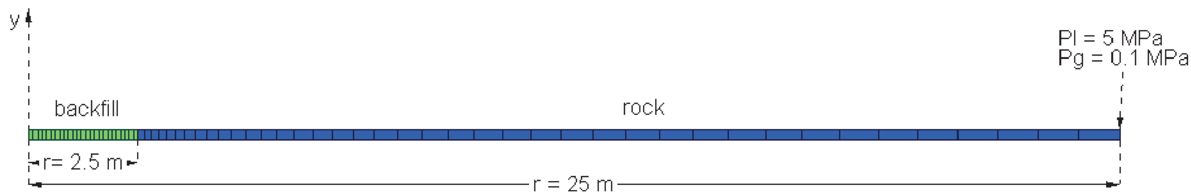
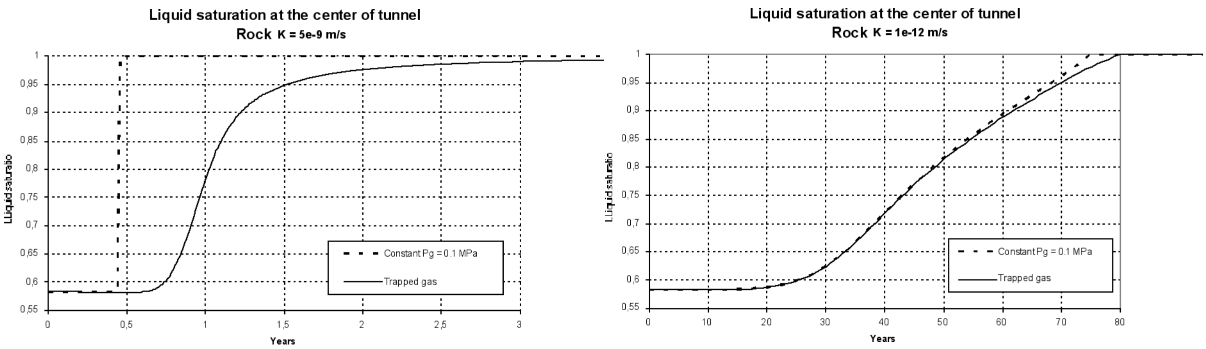


Figure 1: Model geometry, element mesh and hydraulic boundary conditions.

The results suggest that the impact of the trapped air is larger the higher the rock hydraulic conductivity. When the water supply from the rock is large, the trapped air is limiting the saturation rate. This is illustrated in Figure 2, where two cases with different rock permeabilities considering trapped air are compared with corresponding constant air pressure cases. In the high conductive rock case, the saturation time for the trapped air model is about six times longer than that with constant air pressure (Figure 2a). The trapped air inside the backfill forms a "bubble", which holds back the inflowing water. The air pressure inside the "bubble" reaches as high as 5 MPa, which is the same as the water pressure at the model boundary. The only way in which air can escape is by dissolution into the pore water and diffusion through the saturated backfill parts and the rock. Thus, when the water supply rate is high, the saturation process is ruled by the air diffusion rate.

If the rock is tight and supplies little water, the effect of trapped air is small (Figure 2b). The saturation time for the case with constant air pressure is almost as long as for the trapped air case. The water inflow rate into the backfill is sufficiently low that the trapped air has time enough to escape by dissolution and diffusion. The air pressure in the backfill does not reach the maximum value of 5 MPa since the air diffuses away fast enough to limit the pressure build up.



a) **b)**

Figure 2: Impact on the saturation time of trapped air with different assumptions of rock permeability.

The results presented above were obtained under the assumption that the initial, pre-mining gas pressure in the host rock pore water is 0.1 MPa. This assumption may not be completely conservative. Thus, the influence on the backfill saturation process of higher concentrations of dissolved air in the rock pore water has also been studied. These results will be discussed in the article.

MODELLING PREFERENTIAL PATHS OF GAS MIGRATION APPLICATION TO THE GAS MIGRATION TEST

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ABSTRACT

The gas migration test simulates an underground storage concept for medium or low level radioactive waste. A concrete silo was isolated from a granitic host rock by means of a 80/20 compacted sand bentonite mixture. The test was emplaced in a cavern excavated in the Grimsel Rock Mechanics Laboratory in Switzerland. The comprehensive instrumentation installed (piezometers, TDR probes, total pressure cells) has provided information on the barrier performance during the successive stages of the test: emplacement, natural and forced saturation, water injection test and, finally, gas injection tests. Due to the high number of interfaces (buffer-concrete, buffer-rock, surfaces of compacted layers), natural preferential paths are available for gas migration during the final stage of the test.

The paper presents a computer simulation of all the test stages and compares actual field measurements with calculated values. Special attention is given to the simulation of interfaces. This is achieved by means of special continuum elements which simulate gas flow through planar openings. The sand/bentonite mixture was described by means of an elasto-plastic model (BBM). Model parameters were found by means of a backanalysis of suction controlled oedometer experiments on the sand/bentonite compacted samples. Hydraulic laboratory tests (water retention, permeability) were also performed in order to determine the appropriate material parameters.

The computer simulation has covered 6 years of activities and allows an interpretation of the processes taking place in the barrier and the confining rock. It has been shown that water pressurization induces changes of interface permeability. Gas flow paths develop along surfaces which experience an increase of intrinsic permeability. Correlation between zones that undergo irreversible deformations and preferential gas flow paths could be established. It was also found that the established water flow largely controls the paths of gas flow. Figure 1 shows the gas pressure distribution during one of the gas injection tests.

The analysis of the GMT test and the successful comparison with field measurements (pressures, stresses and water content) has shown the capabilities of the model developed to deal with gas migration problems at a large scale. Figure 2 shows a comparison of calculated and measured stresses. It can be seen that the pressure variations due to water and gas injection strongly influence the stress field. The coupling of the two phase flow of water and gas with the mechanical problem was found to be a crucial aspect in the test simulation, specially because the intrinsic permeability variations induced by deformations and the interfaces.

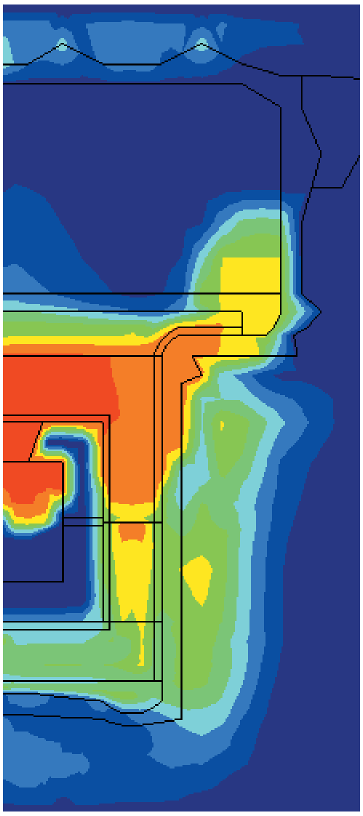

Figure 1: Distribution of gas pressure during gas injection test RGI3.

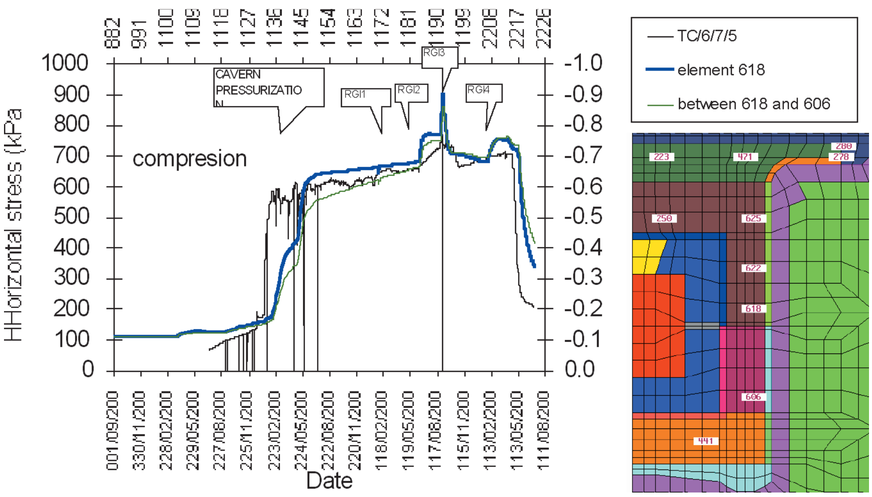

Figure 2: Calculated and measured horizontal stresses in layer 6, i.e. in the backfill between the concrete silo and the host rock.