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Technical Report 15-04

Grimsel Test Site
Investigation Phase VI

Main outcomes and review of the FEBEX In Situ Test (GTS) and Mock-up after 15 years of operation

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G.W. Lanyon, I. Gaus

National Cooperative for the Disposal of Radioactive Waste

Hardstrasse 73
CH-5430 Wettingen
Switzerland
Tel. +41 56 437 11 11

www.nagra.ch

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Map insert

Appendix B Investigations and Evaluation of Slowing of Hydration in Mock-up Test

By M. Villar & P.L. Martín

B.1 Investigations 2000 – 2001

B.1.1 Observed decrease in the water-inlet rate

The decrease in the water inlet rate to the Mock-up was first observed around day 800, as shown in Fig. B-1. Several possibilities were proposed and analysed to explain this behaviour.

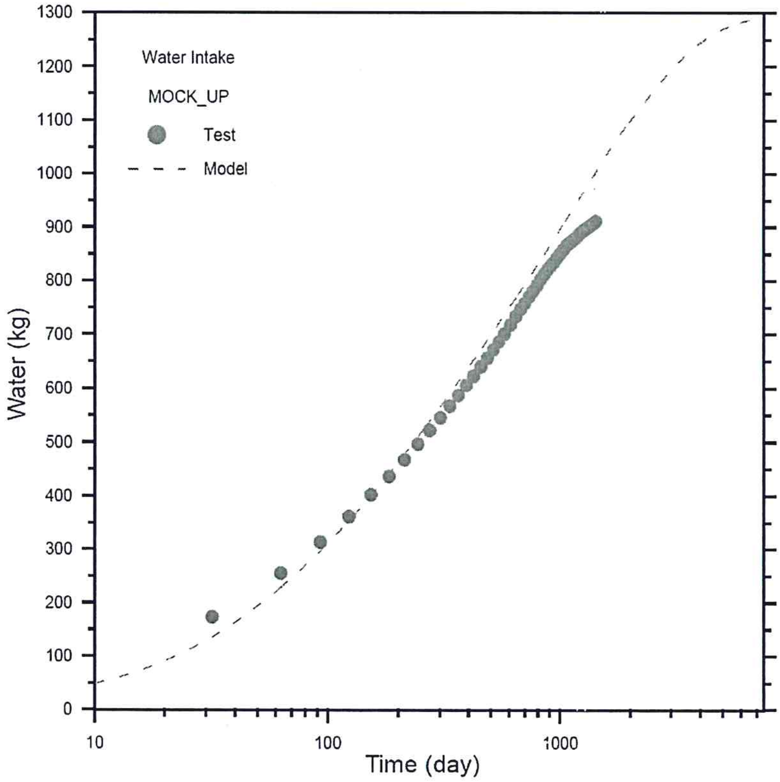

Fig. B-1: Water inlet: measurement vs. model prediction (OBC) for the Mock-up Test.

Clogging of the water injection nozzles

Due to the design of the injection nozzles and the associated system of filters, the possibility of clogging at these points by clay was not considered likely. The system is composed (Fig. B-2) from the outer to the inner part of two sintered metal filters inserted into the nozzle (MOTT Industrial, SS316L, ∅ 6.25 mm, pore size 60 – 100 µm), a mesh disk (SS316L, ∅ 20 mm, n° 100, aperture 0.15 mm) and a geotextile disk (EXXON TERRAM 4000, ∅ 25 mm,). Both disks were glued to the structure.

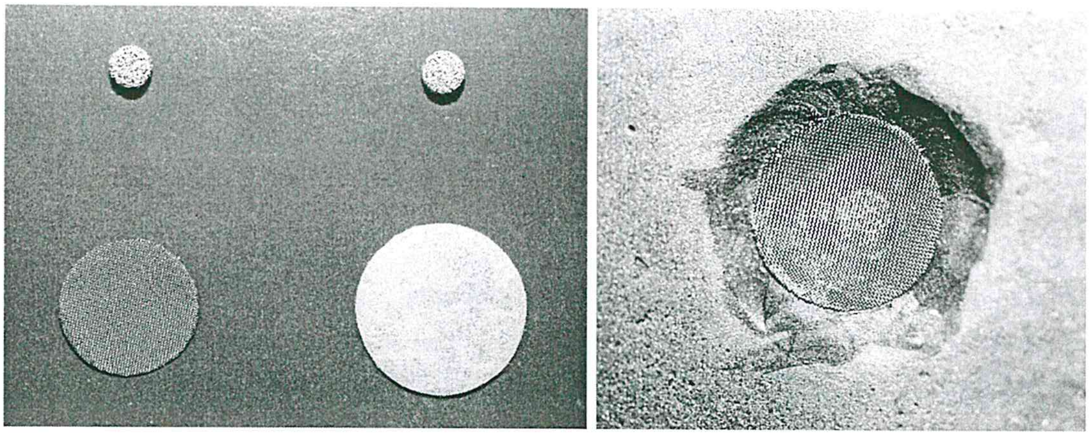

Fig. B-2: System of filters in the injection nozzles for the Mock-up Test.

Clogging of the geotextile layer

Four layers of geotextile cover the inner surface of the structure (Fig. B-3) to assure a distribution as homogeneous as possible of the injection water. The properties of the geotextile (EXXOM TERRAM 4000, thermally bonded non-woven, 70 % polypropylene, 30 % polyethylene) were verified in the laboratory (Villar & Martin 1997) under pressures of up to 5 MPa. Water permeability, both parallel and perpendicular to the layers (around 10^{-8} m/s) and consolidation (more than 50 % volume reduction, non-recoverable) were measured. Temperature (60 °C) did not seem to affect the geotextile properties.

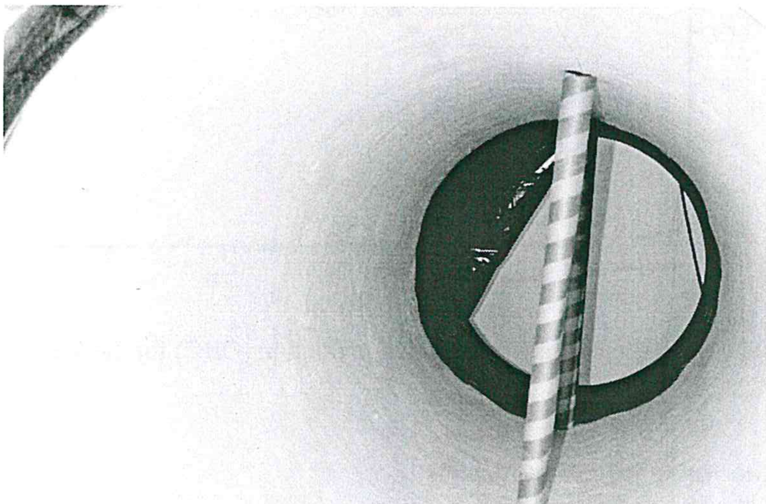

Fig. B-3: Installation of geotextile layers in the Mock-up Test structure prior to bentonite emplacement.

To check if clogging of the geotextile layer had occurred, all 48 valves at the injection points were closed, except two which were located in different hydration rings. Water was injected in one and collected in the other. The amount of water injected as measured by the weighing system was equivalent to the amount of water recovered. This demonstrated that the geotextile layer had high transmissivity under the operating conditions.

In fact, the measured water flow between the hydration rings was much higher than the water flow into the whole EBS as expected from the difference in the water permeability values of the two materials: the geotextile has a permeability six orders of magnitude higher.

System (test) geometry

Due to the geometry of the test, the surface of the hydration front is smaller, as the wetting front goes inwards, which reduces the water intake potential.

B.1.2 Observed decrease of the water pressure

A decrease of the water pressure values in locations connected with the geotextile layers was also detected (Fig. B-4). It began around day 640. Pressures reduced from 5 to 1 bar. The observed pressure decrease is explained by bentonite intrusion into the gaps at the input/output locations in the structure. The bentonite intrusion clogs the active zone of the sensors near these points.

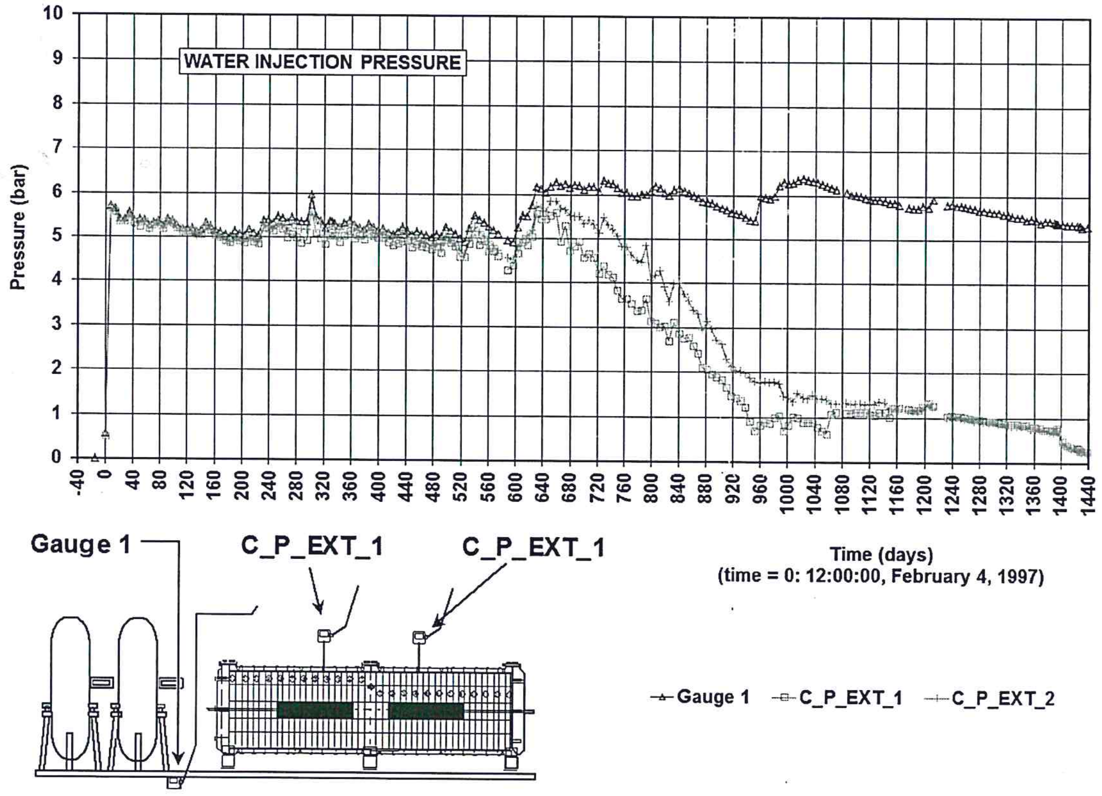

Fig. B-4: Water injection pressure (Mock-up Test).

The geotextile layers were perforated at the input/output locations for the cables, so that at these locations the bentonite is in contact with the structure (Fig. B-5) over a small area (around ∅ 20 mm). The minimum distance from these perforated points to the injection points is 0.25 m. This area is completely covered by the four layers of geotextile compressed by the bentonite swelling. Thus, the possibility of bentonite extruding through the sensor inlets and moving to the injection points is not considered plausible.

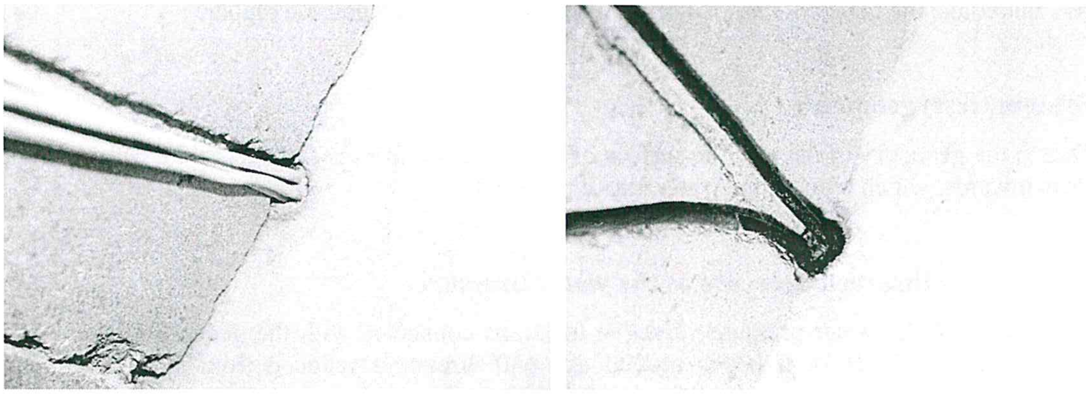

Fig. B-5: Mock-up Test input/output cable locations prior to installation of geotextile.

B.1.3 Observed decrease of the relative humidity

The slight decrease of relative humidity occurred simultaneously with the pressure decrease and several potential causes were analysed:

Gas concentration in the barrier

Gas concentration in the barrier that cannot be dissipated could reduce the progress of the hydration front. Pressurised gas would come from the initial air contained in the porosity of the barrier, from canister corrosion, bacterial activity, or from the hydration circuit (pressurised N_2). However, the fluid pressure sensors that worked correctly during the overheating episode did not indicate any significant gas pressures in the barrier. So, this cause was ruled out.

Anomalous function of the sensors

The evolution of the relative humidity sensors was homogeneous, following similar patterns among them, which indicates that they were working properly. However, an aging process affecting the sensors could not be discarded.

B.1.4 Dynamics of barrier hydration

Several factors affect the dynamics of the barrier hydration:

- **Injection pressure.** The effect of injection pressure is insignificant compared to the high suction of the partially saturated bentonite. At the time when the hydration rate was observed to decrease, the suctions measured close to the hydration surface were well above the injection pressure (10 MPa vs. 0.5 MPa). Currently, the suctions corresponding to relative humidity values slightly higher than 99 % are also above the injection pressure (0.69 MPa vs. 0.5 MPa).

- **Bentonite suction.** It is the main driving force for hydration of the partially saturated barrier. This is true in the zones around the heaters, but it is also important in the almost saturated external zones. As explained above, values of suction similar or higher than those of the water injection can be found in the region of the external part of the barrier considered as "fully-saturated".
- **Bentonite permeability.** In the beginning, permeability was very low but, as the hydration progresses, two opposite processes occur: the relative permeability increases with the increasing saturation and the intrinsic permeability decreases due to the redistribution of the porosity (macro-porosity transforms into micro-porosity). After a first expansion of the outer bentonite, the development of the swelling pressure in the inner zones of the barrier compresses the outer saturated bentonite again, increasing its dry density and, consequently, decreasing its intrinsic permeability.

B.2 More recent work including modelling

B.2.1 Differences between In Situ and Mock-up Tests

Even in the case that "coupled diffusive" processes were exclusively responsible for the energy and mass transfer, the geometric factors are also very important.

1. The external/internal radius ratio of the barrier is much higher in the Mock-up than in the In Situ Test (5 vs. 2.5), which means the behaviour of the Mock-up diverges more from a "plane-sheet" (linear geometry) behaviour than the In Situ Test.
2. The differences between the external temperatures (Mock-up vs. In Situ Test) and the internal temperature (experiment control temperature), along with the above geometric factors result in a slightly different temperature distribution across the barrier in the two tests.
3. The interface between the heater (impervious) and the bentonite is direct in the Mock-up. In the In Situ Test there is a liner along the centre of the bentonite buffer that provides an important void space along the whole experiment for mass transport (with probable piping of gases and water vapour). This gap could be observed in the pictures from the first dismantling.
4. The Mock-up is only hydrated through the curved surface of the confining structure. While the ends of the confining structure are impervious, the In Situ Test is also hydrated through the porous concrete plug and the end of the gallery. The relevance of this difference is given by the existence of a longitudinal liner in the In Situ Test that could favour water migration along its surface (see above).
5. The initial flooding of the Mock-up Test to seal the gaps among blocks provided a homogeneous hydration surface and eliminated the preferential pathways for water and vapour into the bentonite barrier. These preferential paths were present in the In Situ test during an initial period but had largely healed after 5 years (at partial dismantling).
6. There are also significant differences in the overall dry density (Mock-up 1.65 vs. In Situ 1.6 Mg/m^3) that affect the hydraulic conductivity through porosity (and suction).
7. The above points indicate that the processes in the Mock-up was influenced by the limits of the bentonite barrier system (heater walls) significantly before the In Situ Test. The consequence is the slowdown of the processes inside the buffer.

B.2.2 Geotextile considerations

After Palmeria & Gardoni (2000), the factors that could affect the geotextile function are the magnitude of swelling pressure of bentonite against the geotextile, the hydraulic gradient along the geotextile, the physical disturbances on the geotextile (bending, folding, twisting, and crimping), the installation disturbance (gas bubbles), and the permeability of geotextile by intrusion of fine particles termed as filtration and clogging. Physical and installation disturbances can be discarded.

The swelling pressure in the external ring has remained in a narrow range for a long time, hence the progressive compaction of the geotextile due to bentonite pressure can be ruled out.

The initial flow is controlled by the hydraulic gradient and properties of the soil (in this case the bentonite), not by the geotextile-soil system (Gardoni & Palmeria 2002). If we consider that the saturated surface of the compacted bentonite is almost impervious to water, the hydraulic gradient along the geotextile layers must be constant and very low, with no influence on the hydraulic behaviour of the geotextile.

So, the only factor to be considered would be the changes in geotextile permeability due to the initial consolidation phase in the short term, and by filtration and clogging in the long term. The latter process was discarded after the experimental check described in the previous section. Even in the case that the geotextile permeability had reduced during the experiment, it would still be much higher than that of the bentonite, since the initial difference between the two material permeabilities is six orders of magnitude.

B.2.3 Summarised from Villar et al. (2012) and Sánchez et al. (2012a)

From Villar et al. (2012)

Villar et al. (2012) compared different long-term experiments to establish that the rate of hydration of the barrier depends on the bentonite and surrounding media hydraulic properties (that is, water availability), waste temperature and buffer thickness and geometry.

Furthermore, in a large-scale in situ experiment that examined isothermal water inflow from the surrounding granitic rock into highly compacted, unsaturated buffer material, Dixon et al. (2002) observed that, after 6.5 years of operation, the water uptake had been much lower than initially expected. The simulation of this experiment, taking into account the expansion of the microstructure of the bentonite as the material saturated, matched with much greater accuracy both the pattern and rate of water uptake (Thomas et al. 2003).

From Sánchez et al. (2012)

Several studies were carried out to explore possible phenomena that could cause the unexpected barrier behaviour (slowdown in the FEBEX Mock-up Test). Firstly, a wide-ranging sensitivity study found it impossible to obtain a set of constitutive laws and materials parameters (with physical meaning) that led to predictions consistent with the observations. Secondly, it was found that whether the experiment was airtight or not had no influence on the results. Thirdly, the hydration system of the experiment was examined and it was experimentally confirmed that there was no obstruction in the hydration system or geotextile and that the water intake was nearly uniform over the entire hydration front. Similar observations in other experiments support a genuine slowing down of hydration. For example, a lower level of saturation, compared with the expected one, has been observed in the large-scale ITT test performed in the Canadian underground laboratory near Winnipeg. Thomas et al. (2003) concluded that "standard THM models" were not able to capture the slow hydration observed in the experiment.

Experimental evidence indicates that the behaviour of expansive clays under confined hydration is more complex than the conventional THM model used in the numerical analysis. Instead of a progressive increment of the water permeability in external zones of the barrier as saturation goes on, a progressive occlusion of the macro-pores has been observed in the laboratory leading to potentially large reductions in saturated water permeability.

The evolution of the clay fabric (macro- and micro-porosity) is controlled by the changes in the main variables of the problem (displacements, temperature and suction), which are considered in a fully coupled way in the models described by Sánchez et al. (2012a). According to the model results, as the barrier hydration progresses, the macro-pores available to the liquid flow suffer a progressive reduction. This is due mainly to microstructural swelling under confined conditions. As a consequence, the full saturation of the barrier is drastically delayed. This phenomenon affects especially the zones close to the heater, because the reduction of the permeability in the zones close to the hydration front reduces the liquid flow supply to the internal zones, which have been subjected to heating-induced drying.

B.3 Conclusions

The checks performed when the first anomalous behaviour was observed did not indicate any problem in the hydration system. The capacity to supply water to the experiment (via the geotextile) was very much higher than the saturation rate of bentonite.

The differences between the Mock-up and In Situ Test include geometrical, material and operational factors that affect the behaviour of each test. It is also necessary to include the different boundary conditions. Even if the geotextile permeability had reduced during the experiment, it would still be much higher than that of the bentonite since the initial difference between the two material permeabilities is six orders of magnitude.

The double structure model (Sánchez et al. 2012a) is able to simulate the type of hydration locking observed in the test, where significant zones of the barrier may remain in a partially saturated condition for a considerable period of time. However, other physical and chemical phenomena could also influence the slow hydration observed in the clay barrier.