Implementation of the Full-scale Emplacement (FE) Experiment: clay materials, requirements, development and lessons learnt

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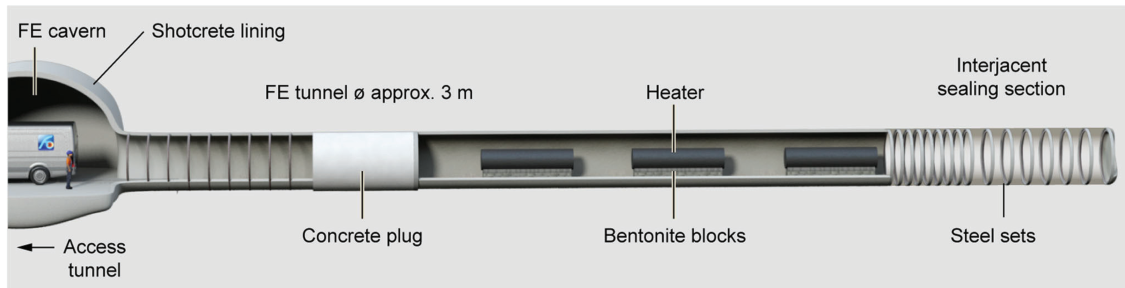
Introduction, objectives and requirements on reference disposal concept



The Full-scale Emplacement (FE) Experiment at the Mont Terri URL is a full–scale heater test in a clay–rich formation (Opalinus Clay) (Müller et al. 2017). It simulates aspects of the construction, waste emplacement, backfilling, and early–stage evolution of a spent fuel / high–level waste (SF / HLW) repository tunnel according to the Swiss concept.

The objectives of the FE Experiment are:

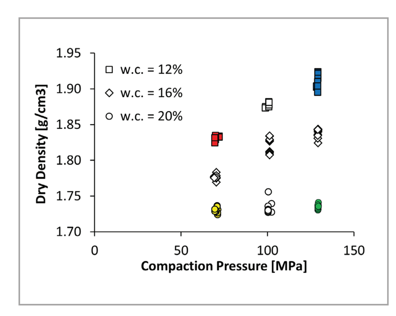
- To investigate SF / HLW repository induced thermo–hydro–mechanical (THM) coupled effects on the host rock at full scale and to validate existing coupled THM models.
- To verify the technical feasibility of constructing a repository tunnel using standard industrial equipment.
- To optimise the bentonite buffer material design and production, in particular to produce bentonite blocks that are capable of resisting the ambient conditions during the storage and operation phases.
- To investigate (horizontal) canister and buffer emplacement procedures for underground conditions.

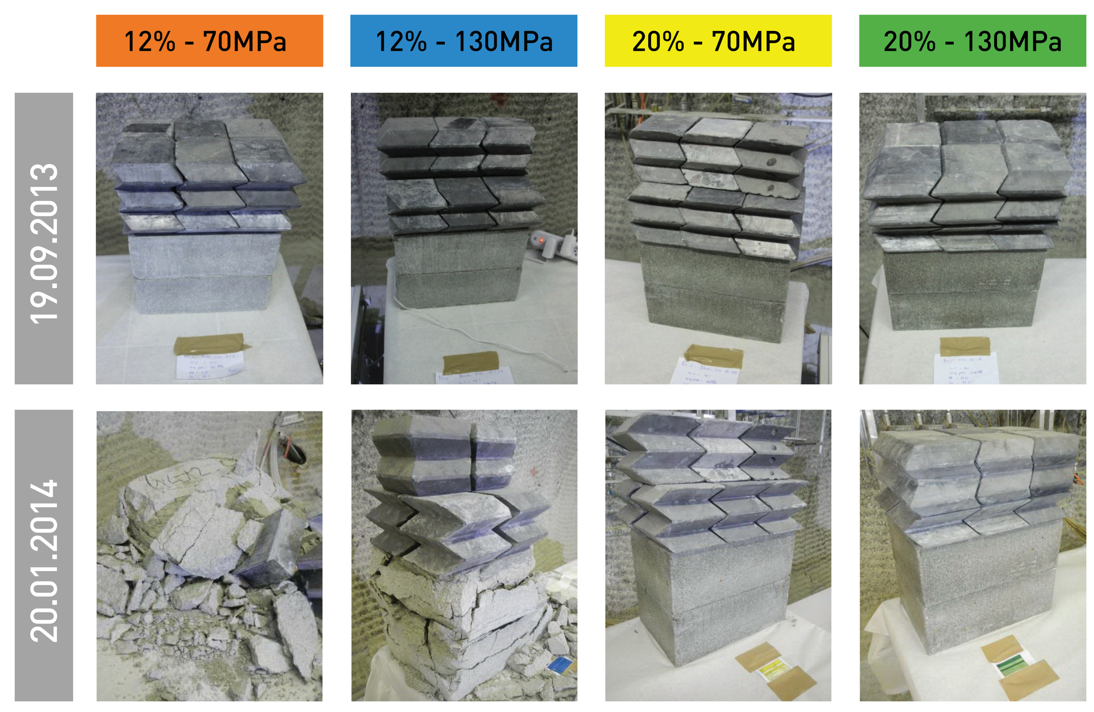
The experiment has iteratively investigated the practical limitations of construction and emplacement technology, and developed requirements on the buffer that are linked to safety functions and to quality control procedures, whilst recognising the demands of developing an industrial production process.

For post-closure safety, the bentonite materials act as a well-defined interface between the canisters and the host rock, with similar properties to the host rock, which ensures that the effects of the presence of the emplacement tunnels and the heat–producing waste on the host rock are minimal, and the bentonite provides a strong barrier to radionuclide transport and a suitable environment for the canisters.

Materials and technology testing programme

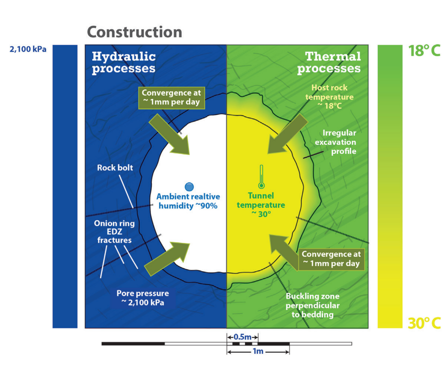
The FE Experiment includes a comprehensive materials testing programme and extensive monitoring of the THM performance of the emplaced materials and host rock. Testing has included, for example, further specification of the granulated bentonite mixture (GBM) buffer, optimisation of the specified water content versus compaction pressure ratio for bentonite blocks (Garitte et al. 2015), and mock-up testing of the backfilling machine to optimise the interaction of backfill quality and the mechanical control system (Jenni and Köhler 2015).



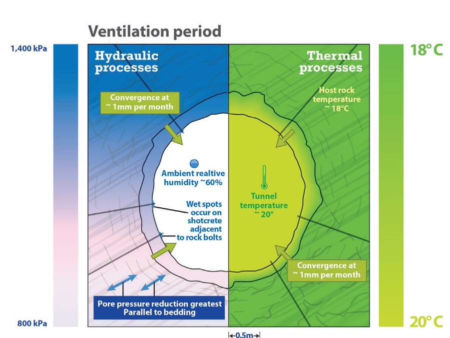


THM processes

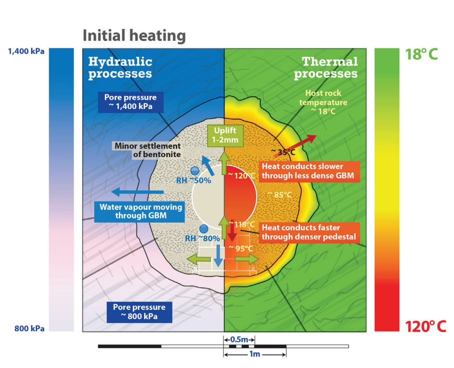
The first 18 months of heater operation has led to significant THM changes to the FE Experiment materials. The main THM processes occurring during construction, during ventilation, in the first two months after the start of heating and in the subsequent period of the Experiment to date are illustrated below. The left side of each figure illustrates the hydraulic changes, the right side the thermal changes and the green arrows the mechanical changes.



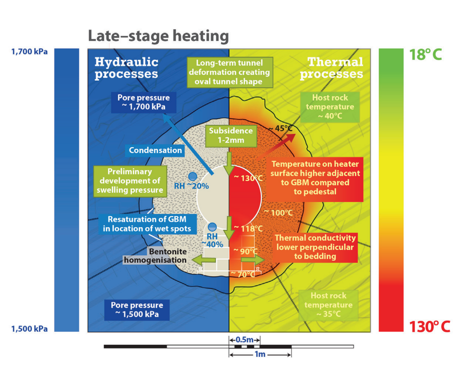
Construction: Development of the EDZ, including a buckling zone perpendicular to bedding and an onion-ring fracture system around the tunnel walls, and convergence of the tunnel wall inwards at an average rate approaching 1 mm per day. The rock is fully saturated and has a temperature of approximately 18°C. The tunnel has an ambient relative humidity of approximately 90 %, and a temperature of approximately 30 °C.



Ventilation: On-going creep of the host rock inwards, but at significantly lower rates. The air in the tunnel is controlled by the ventilation system at approximately 60 % relative humidity and 20 °C.There is minor desaturation of the shotcrete and the host rock closest to the tunnel wall. The rock temperature is unchanged.



Early-stage heating: Heater temperatures increase to 100-120 °C, leading to heating of the bentonite. Temperatures in the GBM close to the heater are higher than temperatures in the bentonite blocks close to the heater. Close to the tunnel wall, temperatures in the GBM are lower than temperatures in the bentonite blocks. Relative humidity of the bentonite is first increased as water moves away from the heaters and then decreases as the impact of the heating reduces saturation further. In the bentonite blocks, which were emplaced with a higher water content than the GBM, the relative humidity remains higher than in the GBM. The heater is subject to uplift of 1-2 mm.



Late-stage heating: The rock begins to heat up, with greater heating in the direction parallel to bedding compared to perpendicular to bedding. The heating is associated with an increase in pore pressure, and this increase is greatest in the direction parallel to bedding. The absolute value of pore pressure parallel to bedding increases to ~1,500 kPa, and the value perpendicular to bedding increases to ~1,700 kPa. The increase in pore pressure is offset by the greater hydraulic conductivity parallel to bedding which leads to water flow into the tunnel.
At this time, the heaters begin to subside, owing to creep of the bentonite blocks and homogenisation of the buffer.

FE experiment-derived requirements

The FE experiment allowed possible new requirements to be identified on bentonite blocks, GBM and the emplacement machine. Translating the results of the FE experiment into formal requirements is ongoing.

Bentonite blocks

The bentonite material shall be sodium bentonite.

Ambient air temperature in the disposal tunnel shall not exceed the equilibrium relative humidity of the bentonite blocks by more than 10 %.

The raw material for production of the bentonite blocks shall have a water content of 19 % ± 1 %.

Production of bentonite blocks shall be produced using a compaction pressure of 130 MPa.

Granulated bentonite mixture

The grain size distribution shall be a Fuller curve with a maximum particle size of 15 mm and a shape parameter of 0.4.

The water content of the bentonite grains shall be 4 - 6 %.

Drying temperatures experienced by the bentonite prior to compaction shall not exceed 80 °C.

The dry density of pellets produced by the compaction process shall be greater than 2 g/cm³.

Emplacement machine

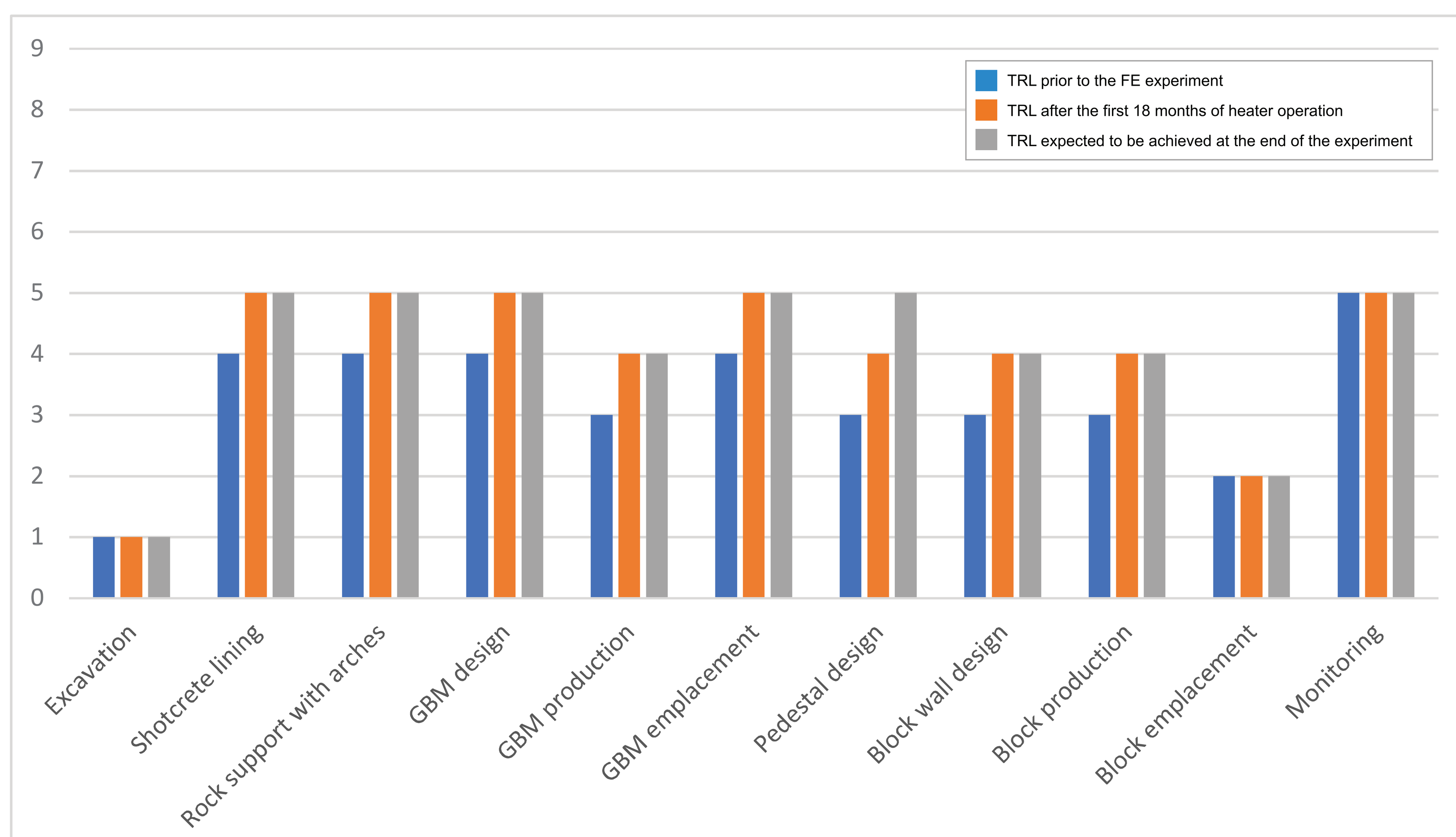
Screw conveyors used to emplace the GBM shall remain in the GBM slope during material emplacement.

Multiple screw conveyors shall be aligned in a staggered manner with respect to the material slope in the backfilled tunnel.

The backfilling machine shall be able to control a high backfilling pressure imparted on the emplaced GBM material.

Technology readiness level

The FE Experiment has contributed to the further development of the readiness of Nagra to dispose of radioactive waste in a deep geological repository in the Opalinus Clay. A technology readiness level (TRL) assessment has been conducted, which considered the main elements of the repository design addressed in the FE Experiment and assigned a TRL for each of three stages: prior to the FE Experiment, after the first 18 months of heater operation, and at the end of the Experiment. This required the development of a repository-specific TRL calibration scheme.



TRL 1: The overall preferred concept to meet the necessary safety functions is described.
TRL 2: Conceptual design drawings, scoping calculations and listing of main THMC processes used to develop preferred concept.
TRL 3: Targeted R&D used to develop preliminary design. May include, for example, identification of material options (candidate materials) for each element of the conceptual design.
TRL 4: Testing of candidate materials or prototype machinery is undertaken in the laboratory or in mock-ups at standalone facilities.
TRL 5: Testing of the candidate materials or prototype machinery in a relevant environment (e.g. a URL in a representative geological environment) in o rder to develop detailed requirements and performance understanding.
TRL 6: Full-scale testing in a relevant environment to demonstrate that requirements can be met; testing used to develop construction procedures and quality control requirements.
TRL 7: Commissioning tests in the operational environment to demonstrate compliance of the detailed design compared to construction procedures and quality control requirements.
TRL 8: Translation of commission test results into documentation and procedures in preparation for implementation.
TRL 9: System operational and successful operational experience developed.

References

Müller, H.R., Garitte, B., Vogt, T., Köhler, S., Sakaki,T., Weber, H., Spillmann, T., Hertrich, M., Becker, J.K., Giroud, N., Cloet, V., Diomidis, N. and Vietor, T. (2017): Implementation of the full-scale emplacement (FE) experiment at the Mont Terri rock laboratory. Swiss Journal of Geosciences, Volume 110, Issue 1, pp 287–306.

Garitte, B., Weber, H. P. and Müller, H. R. (2015). Requirements, manufacturing and QC of the buffer components. Nagra Working Report, NAB 15–24, Nagra, Wettingen, Switzerland and EU Project LUCOEX, Deliverable D2.3. www.lucoex.eu.

Jenni, H. and Köhler, S. (2015). Full-scale emplacement (FE) experiment: Report on the construction, testing and commissioning of the emplacement equipment. Nagra working report, NAB 15-25, Nagra, Wettingen, Switzerland and EU Project LUCOEX, Deliverable D2.4. www.lucoex.eu.