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ULTimateCO_2 project: Field experiment in an underground rock laboratory to study the well integrity in the context of CO_2 geological storage

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Abstract

Wells drilled through low-permeable caprock are potential connections between the CO_2 storage reservoir and overlying sensitive targets like aquifers and targets located at the surface. The wellbore integrity can be compromised due to *in situ* operations, including drilling, completion, operations and abandonment or to geochemical degradation of the caprock-cement-casing system. We present here an experimental set-up in the underground rock laboratory of Mont-Terri (St Ursanne, canton of Jura, Switzerland): the drilling and well completion in the laboratory will be done in the aim of reconstructing interfaces between the caprock, the cement and the casing steel that would be close to the ones observed *in situ*. These well features will then be dipped within a CO_2 stream, during a given time period before a final over-coring. Such an experiment should provide new insights on the quality of bounding between casing/cement/clay interfaces and its evolution due to geochemical reactions. In parallel, a modeling effort is performed focused on both geochemical and transport aspects of the interactions between the fluids and the well compartments.

Keywords: CO_2 geological storage; well bore integrity; transport properties; geochemical degradations; underground rock laboratory

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1. Introduction - context

On a geological carbon dioxide storage site, wells (decommissioned or active) drilled through low-permeable caprock are potential connections between the CO_2 storage reservoir and overlying sensitive targets like aquifers and targets located at the surface. The long term well integrity is therefore essential for the fluids confinements (brine with or without dissolved CO_2 or buoyant gaseous CO_2). Well integrity may be defined as the capacity of the well to isolate fluids in the subsurface reservoirs (Carey & Lichtner, 2011; Crow et al, 2010). The casing and the caprock are bonded by a cement sheet ensuring this isolation; after abandonment, a cement plug is used to avoid upward migration within the casing. Despite this barrier system, wellbore integrity might be compromised in several ways, according to the literature of the subject:

- *Operational defects* - operational defects might be created due to *in situ* operations. During the drilling, the caprock adjacent to the borehole can be damaged leading to potential fractures or other disturbances (Gasda et al., 2008). Cementing process is also important and poor cement-caprock or cement-casing bonding might occur, in case of poor cement mixing or placement, or gas migration during cementing (Zhang & Bachu, 2011). During the life of the well, the pressure and temperature conditions might evolve, changing stress conditions, which might displace the casing, damage the cement sheet and lead to the loss of integrity of the cement sheet and of the bonding with the casing or the host rock (Zhang & Bachu, 2011). The well abandonment might as well lead to potential loss of internal isolation according the method and material used for the well plugging (Watson & Bachu, 2009).
- *Chemical degradation* - cement could be potentially degraded through chemical interactions. In the context of geological CO_2 storage, several chemical environments are likely to exist: dry supercritical CO_2 near the injection well; wet CO_2 (supercritical or gaseous CO_2 in equilibrium with the formation water) and CO_2-rich brine; the two last ones have been shown as the most aggressive environments (Zhang & Bachu, 2011). Cement reactivity is then of first concern and a significant amount of studies have been already carried out to characterize these interactions (for instance Kutchko et al., 2007, 2008, 2009; Duguid and Scherer, 2009; Wigand et al., 2009), but some uncertainties still prevail regarding the impacts on cement degradation (Bachu & Bennion, 2009). Casing corrosion with CO_2 has also been studied as a potential reaction impacting the wellbore integrity (Carey et al, 2010).

The operational defects and the potential degradations due to geochemical interactions may constitute leakage pathways through which fluids might flow. The potential pathways location in the wellbore environment can be summarized as such:

- Migration through damaged zone in the caprock;
- Migration through the caprock/cement interface;
- Migration through degraded or fractured cement (sheet or plug);
- Migration through the cement (sheet or plug)/casing interface.

Given the buoyant character of CO_2 associated to a potential overpressure due to the leakage (driving force), the hydraulic properties of the wellbore environment (especially the effective permeability) and their evolution across time appear to be the main variables in the view of assessing the long term risks of CO_2 storage. So far, this issue was investigated using cement samples or synthetic interfaces and simulating the flow of CO_2 and brine in laboratory (Bachu & Bennion, 2009). The main issue raised by these experiments concerns the representativeness of artificially made interfaces with regards to interfaces encountered *in situ*. Some field studies have assessed the consequences of the contact between wellbores and CO_2 in an EOR field (Carey et al., 2007) and at a natural CO_2 reservoir (Crow et al., 2010). The studies highlighted in particular the lack of integrity that may occur at the interfaces rather than through the cement matrix. Additional studies aiming at assessing the hydraulic properties of the wellbore environment designed system to measure the "effective well permeability" (Gasda et al., 2008).

According to the state of the art, it appears that the multiple potential pathways require the study of the whole well-system. Moreover, the complex geochemistry in the well-environment and its influence on the migration across the pathways needs to be assessed in the meantime to have a good picture of the problem. Laboratory experimentations offer the opportunity to assess the phenomena across time, whereas field observations allow an assessment of the entire system in subsurface. We present here an experimentation in an Underground Rock Laboratory (URL), which will allow both to retrieve the essential well features (caprock/cement/casing/cement compartments) and to follow closely its evolution when in contact with CO_2.

2. Purposes of the experimentation

According to the problem stated above, our objectives are threefold:

- evaluating the hydraulic and transport properties of the well environment built in accordance to existing well standards (assessing the bounding quality across and between the well compartments due to operational defects);
- evaluating the interactions between CO_2 (and formation fluid) and the well environment (close formation, cement, casing);
- assessing the consequences of the interactions on the transport properties of the well environment.

According to these objectives, the experimental setup consists of a wellbore drilled within the Opalinus Clay of the Mont-Terri URL (see Figure 1), which is a well-documented caprock type formation. The drilling and well completion in the field will be done according to the actual standards in the aim of reconstructing interfaces between the caprock, the cement and the casing steel that would be close to the ones observed *in situ*. These well features will then be dipped within a neutral gas stream and then in a CO_2 stream; the experiment will be monitored, following key parameters at different levels (pressure, temperature) as well as sampling fluids at regular intervals. The experiment is planned to last two years. At the end of the contact, the well (and clay vicinity) will be over-cored in order to carry out several characterizations in lab: petro-physical and mineralogical characterizations will thus allow pointing out evidences of leakages and degradations.

In parallel with the experimental work, a modelling effort is performed focused on both geochemical and transport aspects of the interactions between fluids and well compartments. The calibration of numerical models against experimental results will be performed all along the duration of the experiment. The long-term integrity of well environment will be then tentatively tackled by means of adapted modelling and extrapolating tools, including uncertainties assessment and propagation.

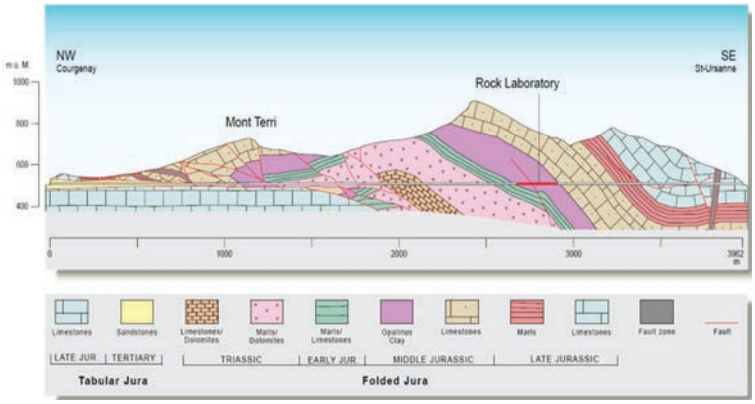

Figure 1: Mont-Terri anticline, after Mont Terri project website, 2011[†]

3. Experimental plan

The experiment plan is made up of the following phases:

- Drilling and well completion;
- Well and equipment testing;
- Hydraulic parameters assessment with use of inert gas;
- Hydraulic parameters assessment over time with use of CO_2;
- Overcoring.

The layout of the experimentation is presented in Figure 2. The dimensions (borehole diameter, casing diameter, cement sheet thickness) were chosen to be close to classical oil wells. The depth was chosen to find a compromise between the maximum overcoring depth and the fact that at too low depth, the excavation perturbations are high in such gallery.

As shown in Figure 2, the well is made of a casing (stainless steel, J55), a cement sheet and a cement plug. The cement used is a class G cement provided by Lafarge. In addition to the classical features, the layout includes the following elements:

- A contact interval for the gas to be in contact with the well features. The pressure and temperature of this interval can be controlled;
- Observation intervals where the changes due to potential leakage inside and outside of the casing will be monitored: sampling and pressure measurement are possible is this chamber; pressure control in the chamber is also possible in order to modify the pressure gradient between the contact interval and these intervals if needed.
- Surface equipment: the surface equipment will allow sampling in all intervals (contact interval, and observation interval 1 and 2), monitoring of pressure and temperature in all intervals, injecting fluid or gas in all intervals, heating the contact interval and keeping the temperature constant

[†] Mont Terri project website: http://www.mont-terri.ch/

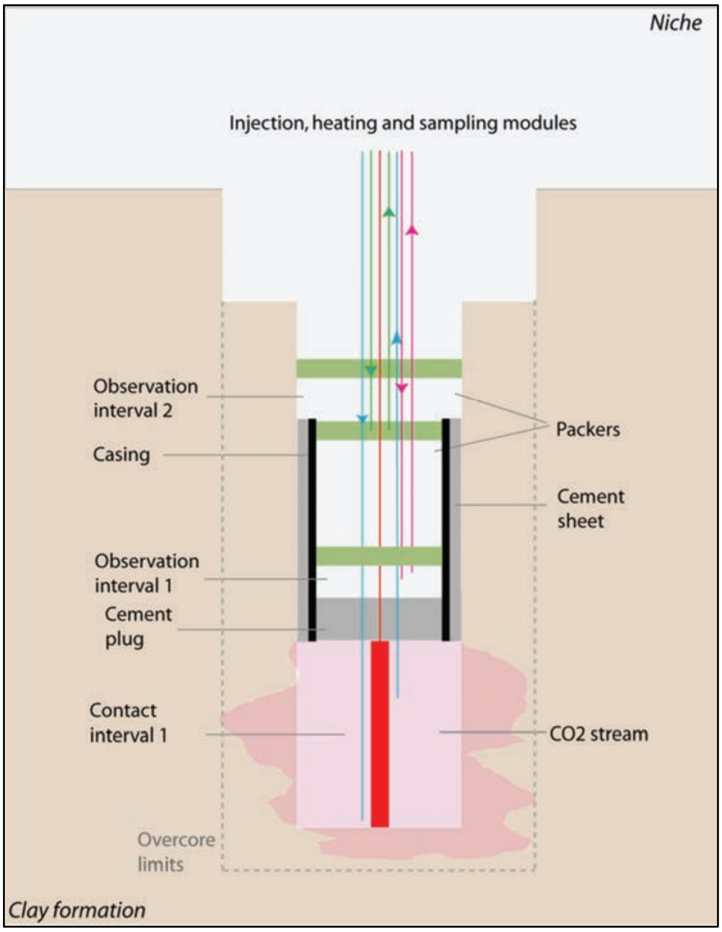

Figure 2: Schematic layout of the experimental set-up (not to scale)

According to the layout, the concept for observing leakages through the wellbore is the following:

- measurement of injected gas or fluid mass into the contact interval;
- monitoring the pressure responses within the observation intervals 1 and 2;
- observation interval sampling and analysis for tracers added to the injected fluid or gas.

After having checked the equipment, the test programme will be divided in:

- short first test phase aiming at assessing the well transport properties for inert gas;
- a second (and main) phase aiming at assessing the consequences of putting the well in contact with CO_2 to characterize the geochemical interactions and their consequences on the well transport properties.

After the main experiment, the final stage will consist in overcoring the well-environment in order to obtain a core containing the interfaces after the contact. Overcoring operations have been already performed for other types of applications (Koroleva et al., 2011) and will provide a complete set of data to be used to build a comprehensive reactive model or to constrain existing ones (Tournassat et al., 2011). Multi scale characterizations will be carried out during the present study in order to point out centimeter to micrometer depth interaction. The combination of different techniques will allow (i) the identification of mineralogical changes including the formation of poorly crystallized materials, (ii) the observation of microstructural changes, (iii) the quantification of the scale of diffusion processes at the interface. Among the used techniques, XRay diffraction, SEM coupled to raman, CEC evolution, leaching experiment will be used on both powder and resin impregnated samples.

In parallel to this experiment, the reactivity of the cap rock as well as of the cement will be studied in laboratory. The laboratory work will include

(i) the initial petrophysical, mineralogical and geochemical characterization of cap rock and cement as well as the initial chemical characterization of brine to be used for the experiment on site;

(ii) the experimental assessment of CO_2-rich brine/cap rock/cement interactions by exposing cap rock/cement to CO_2-rich brine at on site conditions (temperature, pressure) with experimental setup (autoclave);

(iii) the evaluation of reactions/reaction kinetics encountered in (ii) and their impact on cap rock and cement integrity by using petrophysical, mineralogical and geochemical characterization of cap rock/cement as well as chemical characterization of brine after experiment.

4. Modeling work

The modeling will be divided in two tasks: i) multiphase flow and transport modeling (MFTM), and ii) geochemical and reactive transport modeling (GRTM) in order to capture all the phenomena occurring during the test. Uncertainty and sensitivity analysis will be systematically included in the numerical approach in order to maximize the integration between information coming from experimental determinations, numerical calculations and application of fundamental Earth Science principia.

MFTM will be primarily focused on the prediction of fluids migration along the different compartments of the experimental apparatus, and then on the assessment of the hydraulic integrity and long-term sealing capability of both caprock and cement materials. This will involve a specific investigation of the role of discontinuities (e.g. faults, fractures, joints) and interfaces as possible preferential leakage paths for gaseous CO_2 and/or CO_2-charged aqueous solutions.

GRTM will be primarily focused on the prediction of mineralogical alterations induced by the interaction between the different media and gaseous CO_2 and/or CO_2-charged aqueous solutions. Again, the role of discontinuities and interfaces as preferential leakage paths will be of major interest, as well as the feedback of mineral precipitation/dissolution reactions on hydraulic properties of the media.

Given the complexity of the experiment geometry, a fine mesh will be employed to model multiphase flow. GRTM is intrinsically process-oriented and will be focused on the analysis of chemical interactions occurring in the experiment. Due to the high computational cost of GRTM simulations, geometries will be then kept as simple as possible, and eventually different from those used for MFTM.

The modeling work will be organized in four different phases: i) definition of the initial state; ii) predictive modeling; iii) iterative calibration of the numerical models; iv) long-term extrapolation of experimental and short-to-medium term numerical results.

Definition of the initial state

Based on in-situ determination of physical, hydraulic, chemical and mineralogical parameters, a preliminary characterization of media transmissivity and fluids-rock equilibria (aqueous speciation, and saturation state of minerals) in the different compartments (cement and caprock) will be performed under pre-CO_2 injection conditions. The main goal of this phase is to achieve a complete physico-chemical characterization of the materials.

Predictive modeling

On the basis of the information collected during the previous phase, numerical simulations will be performed to define preliminary evolutionary scenarios of the investigated system. The main goal of this phase is to identify the parameters that are expected to control the hydraulic and geochemical evolution of the system.

Calibration of the numerical models

The comparison of the predictive model results with monitoring observations will be the basis for an iterative refinement of the numerical model. The main goal of this phase is to achieve a better understanding of the intricate processes occurring in the system under investigation, and to obtain reliable site-specific parameters usable for further numerical modeling.

Long-term extrapolation

Hydraulic and geochemical fundamental parameters updated through the experimental characterization of over cored materials will be used to explore the sensitivity of the numerical outputs with respect to different initial and boundary conditions, and to perform long-term numerical extrapolations of the observed patterns. The main goal of this phase is to make coherent, and eventually reliable, predictions over larger times than those of the underground experiment.

Conclusion

In this work, we propose to develop an integrated framework constituted by field experiment, laboratory analysis and observations, and modeling in order to get better insights into the conditions of a good well integrity. A field experiment is thus being currently set-up in the URL of Mont-Terri (St Ursanne, canton of Jura, Switzerland). The experimental setup consists of a wellbore drilled within the Opalinus Clay, which is a well-documented caprock like formation. The drilling and well completion in the field will be done in the aim of reconstructing interfaces between the caprock, the cement and the casing steel that would be close to the ones observed *in situ*. These well features will then be dipped within a CO_2 stream; the experiment will be monitored, following key parameters at different levels. The experiment is planned to last two years. At the end of the contact, the well (and clay vicinity) will be over-cored in order to carry out several characterizations in lab: petro-physical and mineralogical characterizations will thus allow pointing out evidences of leakages and degradations. In parallel with the experimental work, a modeling effort is performed focused on both geochemical and transport aspects of the interactions between fluids and well compartments.

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References

Bachu, S., Bennion, D.B. Experimental assessment of brine and/or CO_2 leakage through well cements at reservoir conditions. *International Journal of Greenhouse Gas Control* 2009; 3 (4), 494–501.

Carey, J.W., Lichtner, P.C. Computational studies of two-phase cement/CO_2/brine interaction in wellbore environments. *SPE Journal* 2011; 16(4), pp.940-948.

Carey, J.W., Svec, R., Grigg, R., Zhang, J., Crow, W. Experimental investigation of wellbore integrity and CO_2-brine flow along the casing-cement microannulus. *International Journal of Greenhouse Gas Control* 4 2010; (2), 272–282.

Carey, J.W., Wigand, M., Chipera, S.J., WoldeGabriel, G., Pawar, R., Lichtner, P.C., Wehner, S.C., Raines, M.A., Guthrie Jr., G.D. Analysis and performance of oil well cement with 30 years of CO_2 exposure from the SACROC unit, west Texas, U.S.A. *International Journal of Greenhouse Gas Control* 2007: 1 (1), 75–85.

Crow, W., Carey, J.W., Gasda, S., Williams, D.B., Celia, M., Wellbore integrity analysis of a natural CO_2 producer. *International Journal of Greenhouse Gas Control* 2010; 4 (2), 186–197.

Duguid, A., Scherer, G.W. Degradation of oilwell cement due to exposure to carbonated brine. *International Journal of Greenhouse Gas Control* 2010; 4 (3), 546–560.

Gasda, S.E., Nordbotten, J.M., Celia M.A. Determining effective wellbore permeability from a field pressure test: a numerical analysis of detection limits. *Environ Geol* 2008; 54:1207–1215

Koroleva, M., Lerouge, C., Mäder, U., Claret, F., Gaucher, E. Biogeochemical processes in a clay formation *in situ* experiment: Part B - Results from overcoring and evidence of strong buffering by the rock formation. *Appl Geochem* 2011; 26:954-966

Kutchko, B.G., Strazisar, B.R., Dzomback, D.A., Lowry, G.W., Thaulow, N. Degradation of well cement by CO_2 under geologic sequestration conditions. *Environmental Science & Technology* 2007; 41 (12), 4787–4792.

Kutchko, B.G., Strazisar, B.R., Huerta, N., Lowry, G.V., Dzombak, D.A., Thaulow, N.. CO_2 reaction with hydrated Class H well cement under geologic sequestration conditions: effects of flyash admixtures. *Environmental Science & Technology* 2009; 43, 3947–3952.

Kutchko, B.G., Strazisar, B.R., Lowry, G.V., Dzombak, D.A., Thaulow, N. Rate of CO_2 attack on hydrated Class H well cement under geologic sequestration conditions. *Environmental Science & Technology* 2008; 42, 6237–6242.

Tournassat, C., Alt-Epping, P., Gaucher, E.C., Gimmi, T., Leupin, O.X., Wersin, P. Biogeochemical processes in a clay formation *in situ* experiment: Part F - Reactive transport modelling. *Appl Geochem* 2011; 26:1009-1022

Wigand, M., Kaszuba, J.P., Carey, J.W., Hollis, W.K. Geochemical effects of CO_2 sequestration on fractured wellbore cement at the cement/caprock interface. *Chemical Geology* 2009; 265 (1–2), 122–133.

Zhang, M., Bachu S. Review of integrity of existing wells in relation to CO_2 geological storage: What do we know? *International Journal of Greenhouse Gas Control* $_2$011; 5:8$_2$6–840