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TIMODAZ

Thermal Impact on the Damaged Zone around a Radioactive Waste Disposal in Clay Host Rocks

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INTEGRATION OF TIMODAZ RESULTS WITHIN THE SAFETY CASE AND RECOMMENDATIONS FOR REPOSITORY DESIGN (D14)

Final report of WP6

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TABLE OF CONTENT

1 Introduction

Disposal of high-level and long-lived radioactive waste in deep clay formations is one of the promising options to manage radioactive waste. Analysis of the safety of modern geological disposal system in clay formations highlights the role of the host clay formation as the dominant barrier to delay and attenuate radionuclide (RN) release. To ensure the maximal protection of the environment and the human beings against radiological effects, all disturbances to the host clay over a time span that may extend over hundreds of thousands of years, should be evaluated to ensure the fulfilment of the safety functions of the host clay.

The construction of the disposal infrastructure and operation of the repository, and the emplacement of heat-emitting radioactive waste, will inevitably induce thermal (T), hydraulic (H), mechanical (M) and chemical (C) disturbances to the clay host rocks. One major disturbance is the creation of the so-called Excavation Damaged Zone (EDZ) within the clay formation around the shafts and galleries during the excavation processes. Beyond the characterisation of the initial damage induced by the excavations, the evaluation of the extent and hydro-mechanical behaviour of the damaged zone (DZ) during different repository evolution stages (including the operational period and thermal & post-thermal post-closure stages) is an essential issue in the long-term safety of repositories. The effect of geochemical perturbations in/around the EDZ, including oxidation of the host formation within the fracture zone and the intrusion of an alkaline plume originating from the large amounts of cementitious barrier and auxiliary materials, on the safety-relevant properties of the host clay in combination with the high temperature that the host clay will undergo should also be thoroughly investigated.

The main objectives of the EC TIMODAZ project (Thermal Impact on the Damaged Zone Around a Radioactive Waste Disposal in Clay Host Rocks) is to characterize the impacts of elevated temperatures on the DZ in plastic and indurated clays, during the thermal period. The project focuses on the possible additional damage created by the thermal load, and therefore aims at establishing a sound scientific and technical basis for demonstrating the technologies and safety of geological disposal.

This report integrates the scientific and technical results obtained within the framework of the TIMODAZ project from a performance assessment (PA) point of view, in the context of a safety case. It firstly summarizes the scientific knowledge gained within the TIMODAZ project regarding the impact of the thermal loading on the geological barrier. Then, the knowledge is transferred to the assessment of the safety-relevant properties of host clay. The significance of the DZ within the safety case for disposal in clay host rock is emphasized. Based on the research work previously published and new findings from TIMODAZ, this report updates the description of the expected evolution of the DZ in the geological disposal system for heat-emitting high level waste (HLW) and spent fuel. Recommendations to the repository design and operation are finally addressed.

Throughout this report, the following five key questions form the basis to put the newly obtained knowledge from the project of TIMODAZ [1] into perspective:

1. What is the expected evolution of the DZ around a disposal system of heat-emitting waste during the thermal period?

2. What are the uncertainties on the evolution of the DZ and how can these uncertainties be dealt with?
3. Under which thermal, mechanical and chemical conditions, the favourable clay properties will be modified during the thermal period and how?
4. Under which conditions can modifications of the favourable clay properties become permanent and how much change can there be?
5. To what extent are these alterations of favourable clay properties significant from a PA point of view?

These questions served as a guideline for integrating knowledge between scientists and PA specialists involved in TIMODAZ throughout the whole duration of the project. The answers to these questions provide a comprehensive set of reasoned arguments to support claims about the safety of repositories in clay, or alternatively to highlight remaining knowledge gaps or unsolved problems. These answers may also help the repository designers to maximize the safety margins of the repository system against the inherent uncertainties.

2 Identifying TIMODAZ results that are significant to a safety case

A safety case for the post-closure phase of a geological repository is a synthesis of evidence, analyses and arguments to quantify and substantiate that a repository will be safe after closure and beyond the time when active control of the facility can be relied upon [2]. Demonstrating a sufficient understanding of the system evolution is required within the safety case. Hence, a good comprehension of the inter-related processes occurring within the clay around a disposal system for heat-emitting waste, specifically, the evolution of the DZ during the thermal transient is an essential element of the assessment basis. Beyond the understanding of the general evolution of the DZ, the possible modifications of those favourable clay properties relevant to the safety of the disposal system is of specific interest. These favourable properties include the very low permeability of clays, the small diffusion coefficient of dissolved solutes through the pores, high sorption capacity of clays, the absence of preferential migration pathways for solutes as well as the creep and swelling properties of clays which result in a self-sealing capacity. Together, these properties make clay very efficient at delaying and attenuating radionuclide releases from the waste packages and provide robustness to the disposal system.

2.1 Improved understanding of THM behaviour of host clays

Numerous laboratory tests and in-situ tests have been designed and conducted within the framework of the TIMODAZ project on three types of clay, namely, Boom Clay (BC), Opalinus Clay (OPA) and Callovo-Oxfordian clay (COX). The phenomenological research work improves our understanding of processes occurring within the clay formations of a clay-based geological repository during the thermal phase. The scientific developments and results from the TIMODAZ project promise to strengthen our current understanding with respect to the DZ evolution. The outcome of this project can thus serve as a key reference in the assessment basis for evaluating repository performance and safety in clay formations.

2.1.1. Strong Thermo-Hydro-Mechanical (THM) coupling

Clay exhibits strong coupling between thermal, hydraulic and mechanical behaviours, which is clearly demonstrated once more from in-situ experiments and laboratory tests performed in the TIMODAZ project.

Measurements of temperature and pore water pressure from the **in-situ small-scale heater tests**, SE-H at MONT TERRI Underground Research Laboratory (URL) (Switzerland) and ATLAS III at HADES underground research facility (URF) (Mol, Belgium), give evidences for the strong THM coupling in clay. Figure 1 presents such an example describing variations of pore water pressure with temperature in Boom Clay, as measured in the ATLAS test [3]. The power of the heater was increased in three steps. After each increase, the power was maintained constant. A

rapid increase of pore water pressure is induced at the beginning of each heating. Afterwards, pore water pressure reaches a peak which is followed by a continuous decrease even as the temperature is still increasing (e.g., from Oct. 2007 on in Figure 1). Under a confining environment, a temperature rise temporarily generates excess pore water pressure within saturated clay especially due to the comparatively large thermal expansion coefficient of water. Thermal consolidation occurs simultaneously through pore water dissipating towards the far field as a result of the hydraulic gradient. For a very low permeable porous media like the host clay in the repository system, the excess pore water dissipates rather slowly. This leads to a period with increasing of pore water pressure at the beginning of heating phase. With the decrease of the temperature increase rate (dT/dt), when the thermal consolidation becomes dominant, pore water pressure starts to decrease. The magnitude of the excess pore pressures thus not only depends on the temperature increase, but also is very sensitive to the temperature increase rate [4]. This is even more the case for OPA and COX, which are even stiffer and less permeable than Boom Clay.

Measurements from the in-situ heater test SE-H at MONT TERRI furthermore confirm that the THM coupling is strong in the Opalinus Clay. Figure 2 shows a delay of water pressure rise in the sensor parallel to bedding [3]. On the one hand this is due to the non-symmetric sensor positions. Some contribution to the anisotropic behaviour may also come from the anisotropic properties of the rock. This anisotropic behaviour will be further addressed in section 2.1.4.

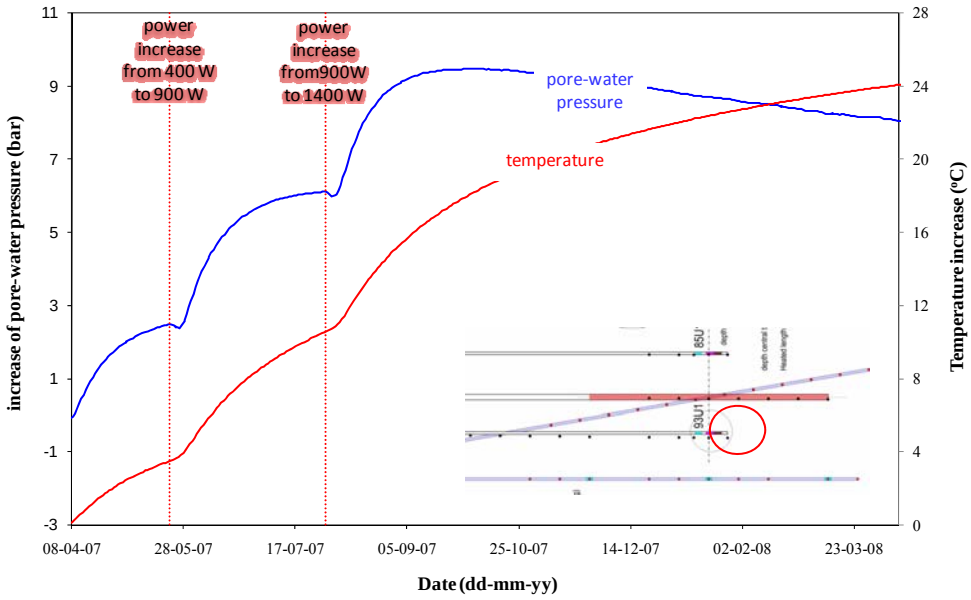


Figure 1: Measurements of pore water pressure and temperature in the borehole AT93E from in-situ heater test, ATLAS III at HADES URF (Distance of porewater pressure and temperature measurements points: 40 cm)

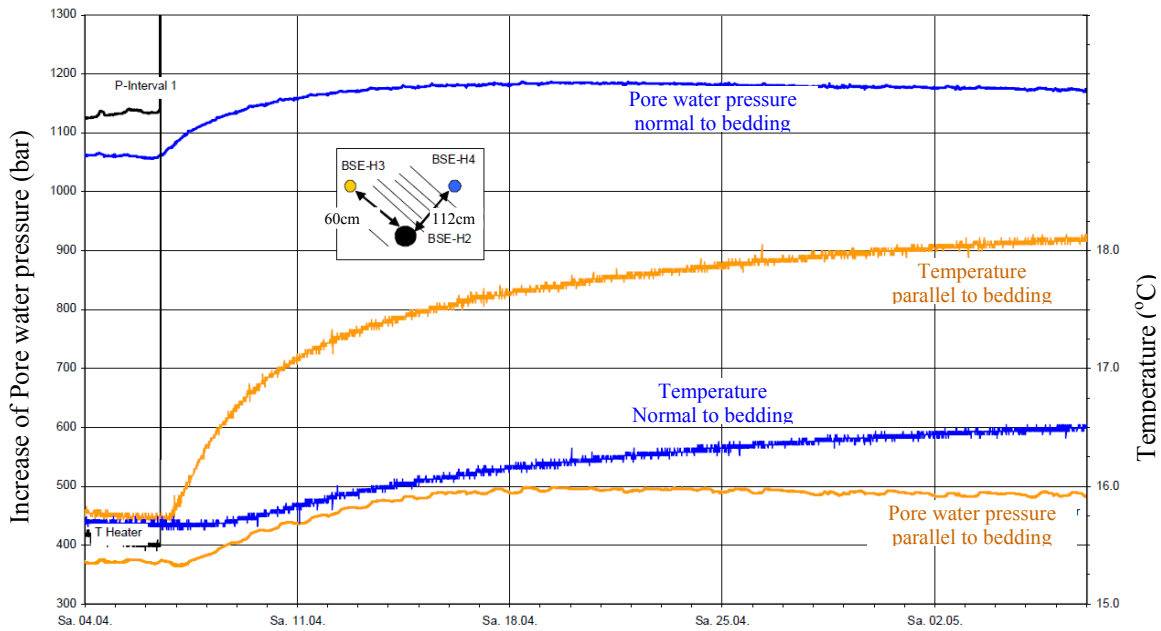
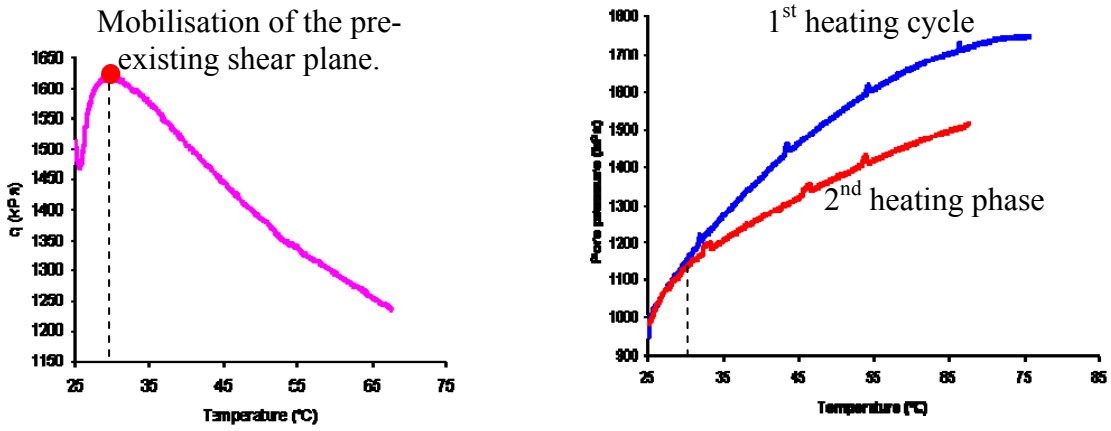


Figure 2: External sensor response during heating step 1 from in-situ heater test, SE-H at MONT TERRI URL

Laboratory tests were carried out to obtain new experimental results on the THM behaviour on BC, OPA & COX in various groups including UJF, EPFL, ENPC, ULG, GRS and SCK [5]. Hollow-cylinder triaxial test performed by ENPC on Boom Clay to investigate the effect of temperature on damage induced by shearing shows the mobilisation of the pre-existing shear plane during undrained heating phase (Figure 3). After an undrained heating phase up to 80°C (1st heating cycle), the sample was sheared to fail with a constant mean stress *p* of 3.25 MPa. The maximum shear stress measured is equal to 2.08 MPa. During the subsequent undrained heating phase (2nd heating phase with a heating rate of 0.017°C/min) with a constant mean stress (p=2.75 MPa) carried on the sheared sample, the shear plane was reactivated once the peak in *q* was reached at 35°C with a value of 1.62 MPa (Figure 3 (a)). Further information can be obtained by considering the thermal pore pressure changes monitored during the undrained heating phases that were carried out before and after shearing (Figure 3(b)). The different response is clearly seen above 35° where the pore pressure increase is less during 2nd heating phase. The failure was probably triggered by a release of effective stress corresponding to a thermal overpressure of the pore fluid on the shear plane [5]. A small decrease of the frictional resistance due to heating was evaluated at the failure plane, with friction coefficient decreasing from 19.5° at peak stress to 17° when failure occurs during the heating test.

This test implies that thermally-induced pore water pressures under undrained (or poor drainage) conditions have an effect on the fissures [5], especially when the mean total stress is not allowed to increase simultaneously with pore pressure. Hydro-fracturing may also happen with severe temperature increase when the thermally-induced pore water pressure reduces the effective stress so much that the structure slips with a smaller shear stress. However, the phenomenon of hydro-fracturing has not been observed in field tests in the TIMODAZ project. Other factors, such as in-situ stress state, temperature increase rate as well as the mechanical boundary conditions (e.g. gallery liner), may make the occurrence of the hydro-fracturing impossible at the repository scale. Observations at the large-scale PRACLAY gallery of the HADES URF are expected to provide more insights on this topic.



(a) (b)

Figure 3: Responses of the 3rd Boom Clay sample during the 2nd undrained heating phase after shearing with constant mean stress (by ENPC)

2.1.2. Thermal-induced plasticity

The drained heating tests under constant confining stress close to in-situ have been conducted in TIMODAZ by ENPC to investigate the thermal behavior of OPA. The test was performed at a heating rate of 1 °C/hr, with a confining stress of 4.1 MPa and a back pressure of 2.2 MPa. The hollow cylinder triaxial apparatus with smaller drainage length was designed to ensure a quick and fully drained condition throughout the test. A thermal dilation between 25°C and 65°C, followed by a contracting response between 65°C and 83°C, was evidenced in the first heating-cooling cycle (Figure 4(a)). In the second temperature cycle, a thermal dilation up to 80°C was observed followed by a contraction during cooling. Irreversible volumetric contraction strains of 0.4 % and 0.12 % were observed at the end of each cooling phase, respectively. This is a typical thermoplastic behavior that once the maximum temperature subjected in the history is overpassed by heating, the dilating-contracting trend no longer appears with a single dilating phase up to 85°C [5].

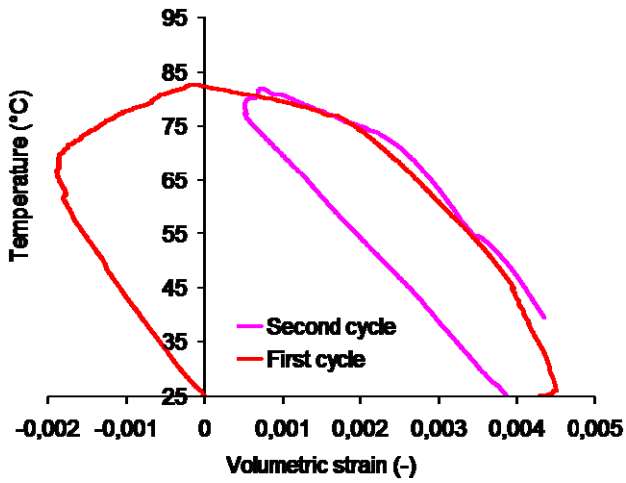
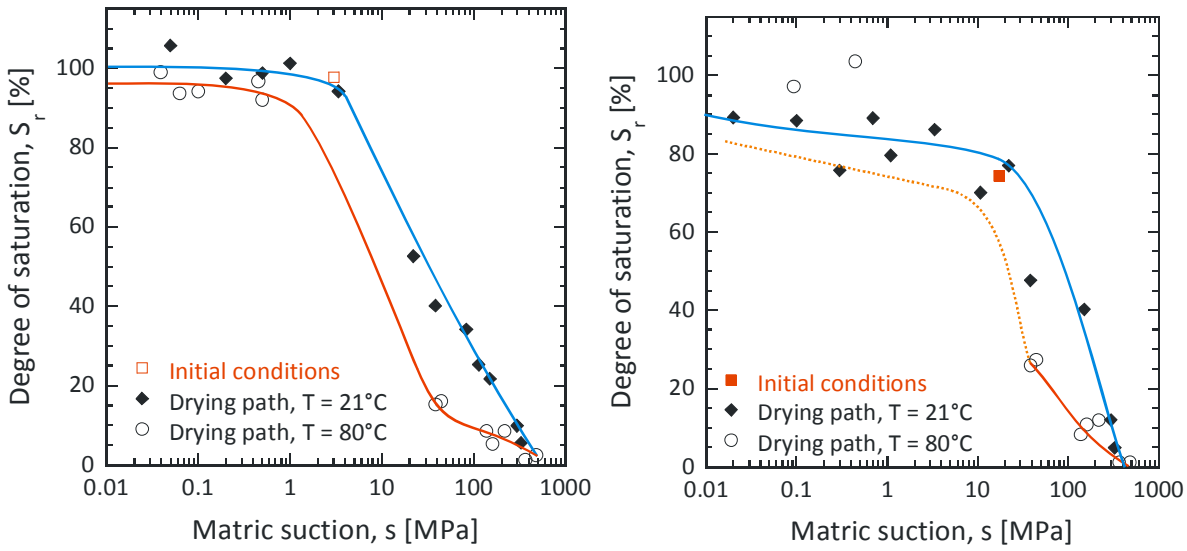


Figure 4: Heating test on OPA under drained conditions with constant confining stress (by ENPC)

2.1.3. Alterations of the water retention capacity

To investigate the evolution of the retention properties of host rocks with temperature, water retention properties at ambient temperature and 80 °C are measured for OPA and the Boom Clay [5]. Comparisons of water retention curve (WRC) at two temperatures in Figure 5 show that WRCs shift left at 80 °C. An elevated temperature clearly reduces the water retention capacity of the material, i.e. under a constant suction above air entry value, the equilibrium degree of water saturation and water content decrease with increasing temperature. The air entry value for Boom Clay decreases from 3 MPa at ambient temperature to less than 1 MPa at 80°C.

After the depletion of oxygen in the Engineered Barrier System (EBS), gas generation is inevitable in the repository system as a result of the aerobic corrosion of ferrous materials in e.g. the waste canisters, liners, etc. The decrease of the retention capacity and air entry pressure of the host clay at elevated temperatures may facilitate pore water displacement by gas during the thermal period if the gas production rate exceeds the capacity of the host rock for diffusive removal of dissolved gas.



(a) Boom Clay (b) OPA

Figure 5: Water retention curves for Boom Clay (left) and OPA (right) at two different temperatures (by LMS-EPFL)

2.1.4. Anisotropic properties

One valuable contribution of the TIMODAZ project is to confirm the role of anisotropy of clay host rocks in various experimental tests [3,6] and to quantify its consequences. The causes of anisotropic behaviour of clay host rocks can be divided into two groups: structural anisotropy which is determined by the sedimentary nature of the clay formed, and initial stress anisotropy.

Numerical modelling campaigns confirm that including anisotropic characteristics in the model does significantly improve the predictive quality and allows capturing finer features of the clay

behaviour exhibited in the tests. Initial stress anisotropy and anisotropic hydraulic conductivity have been already well investigated in the SELFRAC project to explain the experimentally observed anisotropic pore pressure distribution around the connecting gallery at HADES URL [7], therefore we will focus below on the mechanical and thermal anisotropy.

2.1.4.1 Thermal anisotropy

The spatial distribution of the temperature sensors in ATLAS III enables us to quantify the observed thermal anisotropic behaviour of the Boom Clay. The temperature increment parallel to the bedding plane reaches a value higher than that normal to the bedding plane with the similar distance to the heater (Figure 6) [3]. Such a difference is a clear evidence of anisotropic thermal conductivity due to the stratified structure of the clay formation. From the measured temperatures it could be derived that the thermal conductivity equals 1.65 W/(m·K) for the Boom Clay along the bedding plane, and 1.31 W/(m·K) in the normal plane. Thermal anisotropy has earlier also been observed in COX clay [8].Values of the thermal conductivity range from about 1.9 to 2.7 W/(m·K) along the bedding plane and 1.3 to 1.9 W/(m·K) perpendicular to the bedding plane for COX.

The observed thermal anisotropy has consequences for the calibration of theoretical models, and may have an impact on the design of a clay-based repository, as will be elucidated in subsequent chapters.

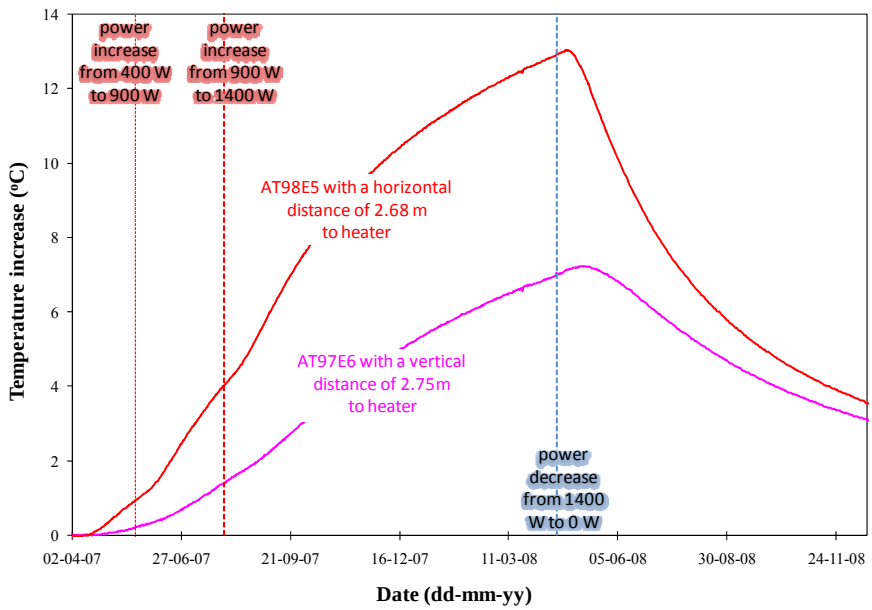


Figure 6: Temperature response from in-situ small-scale heater test, ATLAS III at HADES URL: sensor in the direction parallel to the bedding plane (TC-AT98E5) and in perpendicular direction (TC-AT97E6).

2.1.4.2 The role of mechanical anisotropy in DZ creation and evolution

The resin trace image from the overcoring of SELFRAC experiment at MONT TERRI URL, presents a bedding controlled buckling fracture mode of the borehole damage zone around the SELFRAC borehole as illustrated in Figure 7(a) [3]. The removal of the test system - the SELFRAC dilatometer probe - completely unloads the borehole wall and the borehole collapses. The original borehole is represented by the elliptical opening in the centre of each overcore slice.

The inspection of the entire set of slices shows that the position of the elliptical shape is a result of a larger convergence in the direction normal to bedding and a smaller convergence in the direction parallel to bedding. A sketch of borehole collapse pattern is given in (Figure 7(d)). This collapse structure demonstrates that deformation of argillite is bedding controlled and the EDZ is controlled by the orientation of the gallery with respect to the bedding.

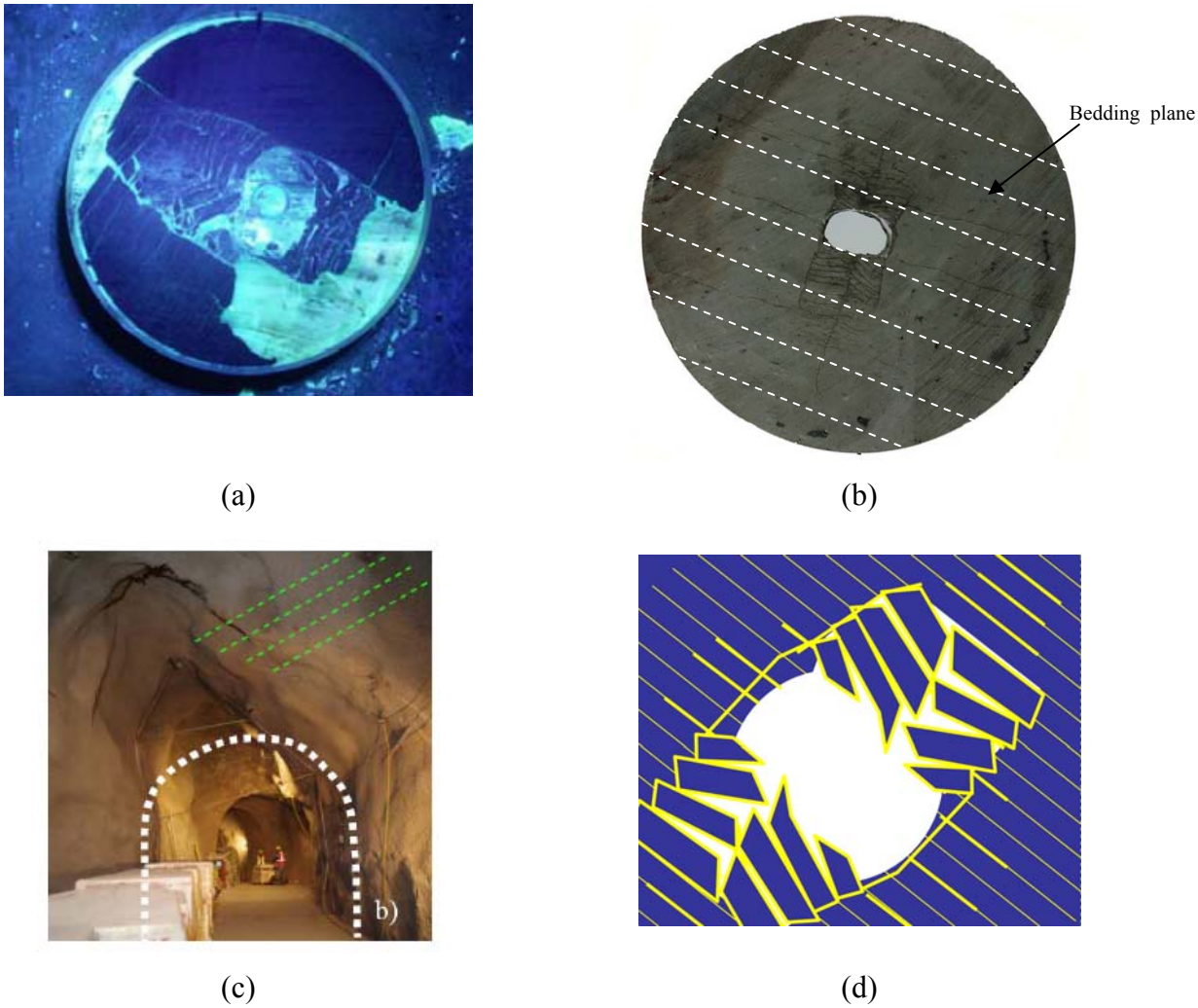


Figure 7: Similar fracture pattern observed in OPA in the (a) small-scale in-situ test at MONT TERRI URL; (b) medium-scale hollow cylinder test N° 12 by EPFL (c)formerly horseshoe type tunnel; (d) A sketch of the borehole collapse structure.

Similar fracturing pattern around the central hole was observed in the medium-scale hollow cylinder laboratory test N°12 on OPA clay performed by EPFL (Figure 7(b)), in which cracks sub-parallel to the bedding planes open and lead to a buckling failure in two regions that extend from the borehole in the direction normal to bedding [6]. Similar fracture pattern is also found around a large-scale in-situ gallery at MONT TERRI URL as shown in Figure 7(c). The consistency among experiments over a range of scales strengthens the confidence when upscaling the laboratory tests to repository-scale tests. However, any upscaling has to take into account the differences in experimental procedure at different scales e.g. rates and techniques of excavation and support application.

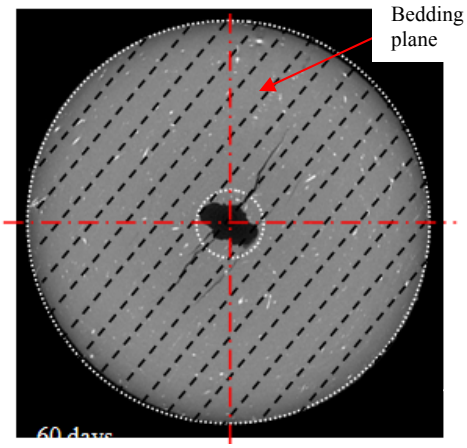
Contrary to OPA clay, a larger convergence happens in the direction parallel to the bedding plane around the central hole in the medium-scale hollow-cylinder tests for Boom Clay carried out by the same Laboratory EPFL (Figure 8(a)) [6]. The total displacement profiles are plotted along diameters parallel, perpendicular and at 45° with respect to the bedding planes by tracking the movement of pyrite (PMT) inclusions in the X-Ray CT images before and after mechanical unloading (Figure 8(b)&(c)). The convergence around the central hole is obviously larger along bedding (purple) than normal to bedding (yellow). The convergence further away from the central hole is found to be larger in the direction perpendicular to the bedding plane than in the parallel one (Figure 8(b)). The displacement profile in (Figure 8(c) shows an abrupt decrease of the displacement along each direction which allows distinguishing a "damaged" zone from the elastic zone. An eye-shaped "damaged" zone is illustrated with an ellipse which has a long axis extending along the bedding plane (the white solid ellipse in Figure 8(c)).

The anisotropic deformation pattern is consistent with the one inferred from measurements recorded in the construction of the PRACLAY gallery of the HADES URF. When the excavation was started, an overexcavation of 81 mm in diameter was realised to counteract in advance the radial convergence of the gallery. The overexcavation on top and at the bottom was found too large due to a smaller vertical convergence. The same phenomenon, convergence is large along the bedding plane but to a less amount, was observed during the excavation of the Connecting Gallery of the HADES URF [9].

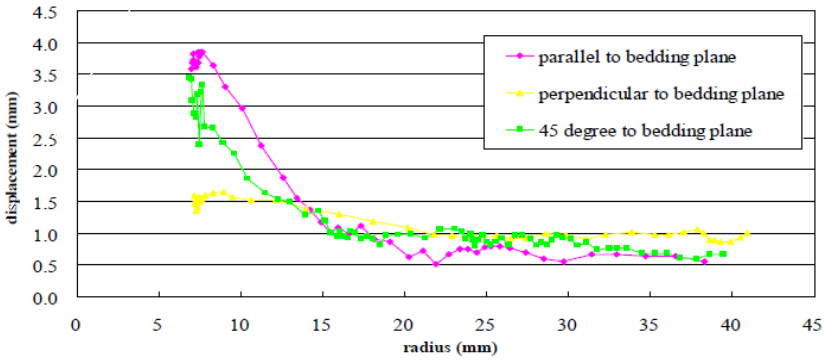
The fracture pattern around the PRACLAY gallery is quite similar to what have been observed in the Connecting Gallery (Figure 8(d)) [9]. It consists of conjugated planes. These fracture planes are curved and the curve is more pronounced vertically than horizontally. The EDZ is thus not symmetrical with respect to the gallery axis and extends a bit more in the horizontal plane (parallel to bedding plane).

Boom Clay and OPA are both transversely isotropic materials, with a smaller stiffness in the direction perpendicular to the bedding plane. When the gallery orients parallel to the bedding plane, the gallery convergence exhibits reverse pattern in two clays. This implies that the DZ also extends in reverse directions in two clays (Figure 9). The difference of the damage pattern exhibited in BC and OPA is most probably a consequence of different failure mechanisms: ductile behaviour in Boom Clay (i.e. shear failure prevails along conjugated planes) and brittle behaviour in the indurated OPA (tensile failure along bedding planes followed by buckling) [6]. The damaged zone around a gallery parallel to the bedding plane in BC is related to the initial anisotropic stress of clay and the subsequent development of an anisotropic plastic zone around the gallery. In the near field of the gallery, a larger deviatoric stress along the horizontal profile due to a sudden release of radial stress during excavation induces a plastic zone about three times deeper along the horizontal profile than that in the vertical profile (Figure 10). Considering mechanical anisotropy and plasticity in the simulation of medium-scale hollow-cylinder test on

BC enables reproducing the similar convergence pattern. However, the deformation in OPA is dominated by elastic deformation which is larger normal to the bedding plane as a result of the lower stiffness of clay in the perpendicular direction (Figure 10) [10].



(a)



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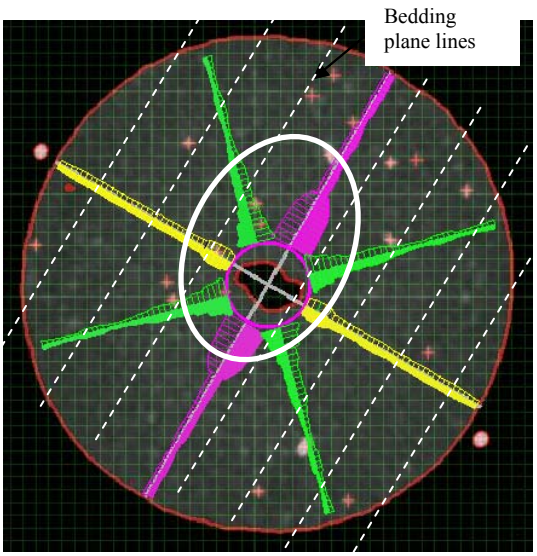

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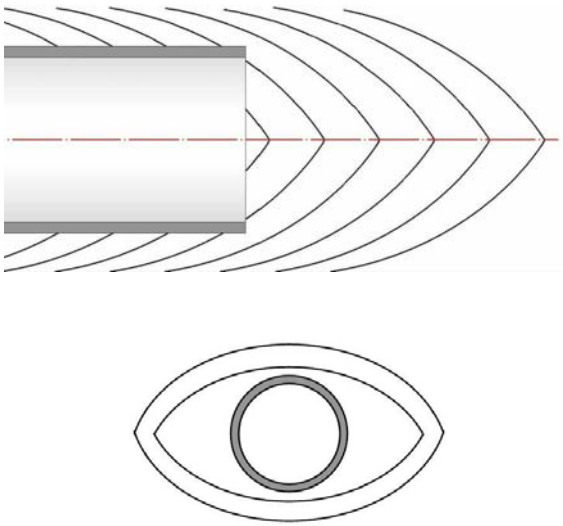


section view

(d)

Figure 8: contrary convergence behaviour around the central hole observed in the (a) Boom Clay 13A by EPFL (b) profile of total displacement in three directions by tracking the movement of pyrite inclusions in CT images before and after mechanical unloading for the experiment 13A (c) displacement profile for the experiment 13B_Bis (d)Excavation induced fractures at HADES URL

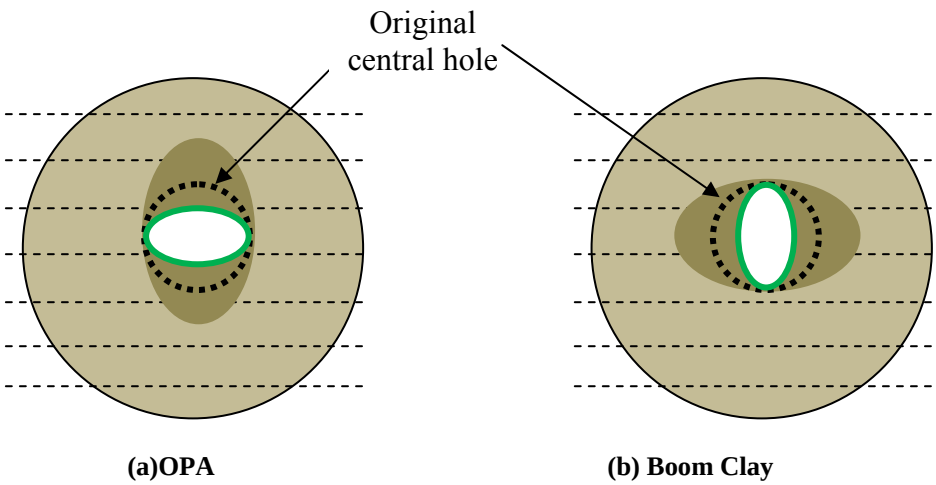


Figure 9: Schematic illustration of the oval-shaped deformation of the central hole (green solid line) and "damaged" zone developed around the central hole (dark brown area) in two clays

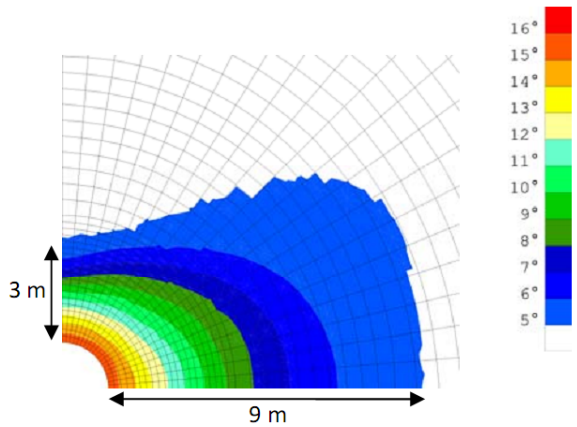


Figure 10: Simulated plastic zone developed around PRACLAY at the end of the excavation based on the 2D plane strain model. Actualized ("hardened") Coulomb's friction angle. Initial value is 5° (in white).

It has already been recognized in the Dossier 2005 [8] that COX clay shows only a slight mechanical anisotropy (with a $\sigma_{hor}/\sigma_{ver}$ anisotropy ratio of 1 to 1.2). Therefore, no significant efforts have been paid in TIMODAZ to investigate on this issue in more detail. GRS has performed several tests, outside the scope of TIMODAZ, to determine the mechanical and hydraulic anisotropies of the COX argillite core samples taken from the Meuse/Haute-Marne Underground Research Laboratory (MHM-URL) in Eastern France [11]. The objective was to provide basic data for modelling the hydro-mechanical response of the argillite to shaft sinking on the basis of uniaxial creep and relaxation tests. The performed tests showed no significant anisotropy effect on the pure creep behaviour for the argillite. The long-term mechanical behaviour of the investigated region of the argillaceous formation was found to be relatively homogeneous. In addition, the significance of the HM anisotropies decreases with confining stress. The issue of anisotropy will be dealt in more detail by GRS within an envisaged research programme.

2.1.4.3 Coupling between thermal loading and mechanical anisotropic behaviours

Figure 11 illustrates a graph of the measurements in borehole AT93E at the ATLAS III in-situ test. It clearly shows that a temporary and relatively small decrease of the pore water pressure was measured at the very beginning of each increase of the heater power. Similarly, an increase of pore water pressure was observed for a short time at the very beginning of heater power shut-down. The same phenomena have been observed at other sensors. The pressure drop (or increase) at any given filter occurs before the temperature increase (or decrease) at that filter.

The delay of the temperature variations to the change of heater power is due to the distance between the sensors and the heater and temperature sensors in the far field need time to respond. In the close up graph in Figure 11, when the power is switched off, the dissipation of the heat goes on and the temperature increase continues. During the lag of the temperature response, the variation of pressure is in fact a consequence of material anisotropy on the HM coupling. As soon as the response of temperature appears, pressure increase (or decrease) occurs as a consequence of THM coupling (illustrated by the green solid line in Figure 11). Numerical work carried out in WP5 concludes that only the case when the cross-anisotropic elasticity is included in the simulation allows catching the temporary water pressure decrease after increasing power and temporary water pressure increase after cooling. The observed pore water pressure variations are of minor importance for PA, but they do confirm that a modelling study which pays attention to a specific feature (here, anisotropy) is hence proved to be helpful in steering the R&D programme (here: effort to better characterise anisotropic properties in Boom Clay).

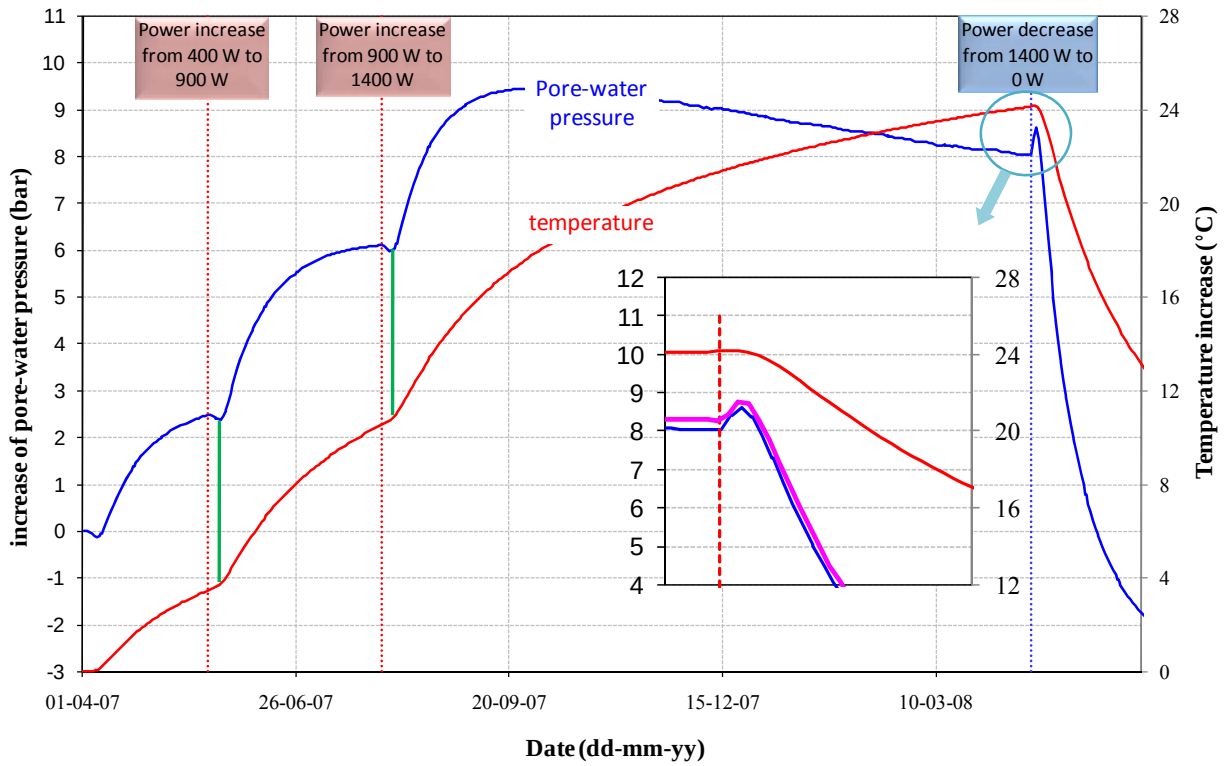


Figure 11: Comparison between increases of pore water pressure and temperature in borehole AT93E at ATLAS III, HADES URF.

The in-situ heater test at MONT TERRI SE-H measured a delayed temperature response in the direction perpendicular to the bedding plane and a delayed pore water pressure response in parallel direction (Figure 2). The temperature response is comparable to the one observed in the ATLAS III heater test and is easy to be explained by anisotropic thermal and elastic properties of the clay material.

2.1.5. Improved test procedures and techniques

The TIMODAZ project has significantly beneficiated from a non-destructive technique, namely X-ray computed tomography (µCT) as systematically used by UJF and EPFL, which allows the experimenter to visualize cracks and discontinuities in clay samples before, during and after testing. This technique indeed showed the pre-existing discontinuities on so-called "intact" samples appeared to be quite significant. Figure 12 shows one example of the state of fissuring in an OPA specimen before testing. µCT reveals multiple parallel fissures in the specimen which have the orientation of the bedding [5]. Boom Clay also presented apparent pre-existing discontinuities that have been probably neglected in former standard soil mechanics investigations not aimed at characterising the specific effects of discontinuities [5].

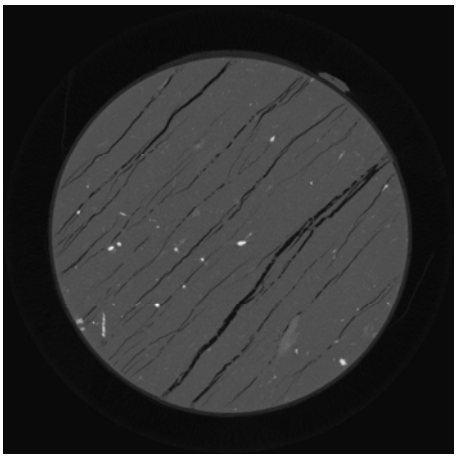


Figure 12: Multiple parallel fissures revealed by the X-rays in an OPA specimen before testing (by UJF)

Observations from µCT confirm that the processes of excavation, storage, transportation, and conservation of clay samples indeed induce some significant effects on samples. Further drying in ambient atmosphere lets the pre-existing fissures grow noticeably in length and width. In this regard, the prevention of drying as quickly as possible after coring (e.g. rapidly wrapping the sample in thermo-folded plastic/aluminium membranes) is of paramount importance to laboratory testing [5].

During the resaturation process of clay samples under free volume and lower confining pressure, many difficulties were encountered due to the pre-existing damage in clay samples, mostly in the direction of the stratification. Triaxial testing on such severely damaged specimens would be of little meaning for extracting constitutive behaviour from the test results [5]. In order to minimize the impact of the pre-existing damage, strict test protocols were defined at the beginning of TIMODAZ to confine the clay sample under a confining pressure close to the in-situ stress state

before resaturation in order to avoid further perturbations due to swelling. (Detailed procedures are described in [5]). These procedures significantly minimized the scattering of the test results. Test results from various groups obtained in TIMODAZ are quite consistent, which much facilitates the subsequent model calibration. But for such a natural material as clay, some irreducible variability always exists in the experiments.

The main objective of the laboratory tests is to characterize the relevant coupled THM processes in clay rocks and to calibrate the THM constitutive models. The existence of the inevitable pre-existing damage in clay samples before testing raises a fundamental question about the interpretation of lab tests results in terms of stress-strain responses which is what the constitutive modelers would like to extract from the tests. The relationship between the parameters measured in the laboratory and those that fit in in-situ is also noteworthy. Another important consequence of the existence of pre-existing damage in clay samples before testing is that the calibrated parameters from lab tests may deviate from their in-situ counterparts and should therefore be used with great caution in case they are applied to full size repositories [5].

From the experiences of TIMODAZ, it is agreed that in practice, there are no strictly drained condition for indurated clay with a very low permeability. Even if one makes abstraction of the different types of water in the clay, the time scale involved for the drainage of even a small scale sample makes that pore water pressure fields in "drained" tests are rarely uniform. In this context, it would be more appropriate to say that the valves to the drainage lines are open during testing in the “drained” tests [5]. The development of new device with small drainage length at ENPC appears promising to gain full saturation and a quick pore pressure homogeneity within the sample thanks to the significantly higher dissipation rates permitted. The fact that there are no strictly "drained" conditions should be taken into account during interpretation/analysis of the test results and thus calibration of the model parameters.

Various high pressure thermal triaxial apparatuses, small and large scale hollow cylinder ttriaxial cells have been specifically designed and manufactured within the framework of TIMODAZ. The very low permeability of the clays tested in the program makes the testing devices very sensitive to leaks and micro leaks. An added technical difficulty is the negative effect of elevated temperature on water tightness [5]. Great difficulties have been overcome by each group to make these new apparatus running properly. In order to make full use of these apparatus, it is worthy to keep them in operation for supplying more valuable data in the future. As more qualified experimental data become available the model calibration can be done more reliably.

To study the development and the evolution of the damaged zone induced around the central hole in hollow cylinder tests, two image processing tools have been applied by EPFL to reconstruct the displacement field: Particles Manual Tracking (PMT) of pyrite inclusions present in the clayey material and Digital Image Correction (DIC). By comparing the position of pyrite inclusions in the CT scans before and after the mechanical unloading, it allows quantitative analyses of the undergone displacements. 3D Volumetric DIC has been applied to the x-ray CT images before and after mechanical unloading to provide incremental displacement and strain fields. Detailed descriptions of these imaging tools are available in [6].

2.2 Safety-relevant aspects of THM perturbation and evolution

As the dominant barrier in the multi-barrier system of a repository, the geological formation around the disposal galleries contributes to the safety of the geological disposal system by fulfilling the safety functions of isolation, confinement and retardation. Specifically speaking, with respect to the geological formation, the major safety functions of the geological formation comprising the repository system are (1) to limit the water flow through the system so as to ensure that the dominant transport mechanism in the near field is diffusion; (2) to retard radionuclide migration due to physical-chemical processes such as sorption and contaminant precipitation. These features ensure that most RNs decay to negligible quantities within the host formation and only a small fraction will ever reach the biosphere.

The fulfilment of the above safety functions depends inevitably on the maintenance of some favourable properties of the host clay: the very low permeability, the small diffusion coefficient of dissolved solutes through the pores, high sorption capacity of clays, the absence of preferential migration pathways for solutes as well as the self-sealing capacity. In this section, these safety-relevant aspects will be evaluated to see if the clay host rock is still able to fulfil its safety functions after experiencing THM perturbations.

2.2.1 More evidences of the self-sealing capacity of clay at room temperature

A good self-sealing capacity is an important feature of a geological barrier material as it helps to maintain low permeability property by limiting the evolution of preferential pathways even after various perturbations. Pore water and smectite content are indispensable to the development of self-sealing in clay, while compressive pressure and visco-plastic deformation are very helpful to the development of self-sealing.

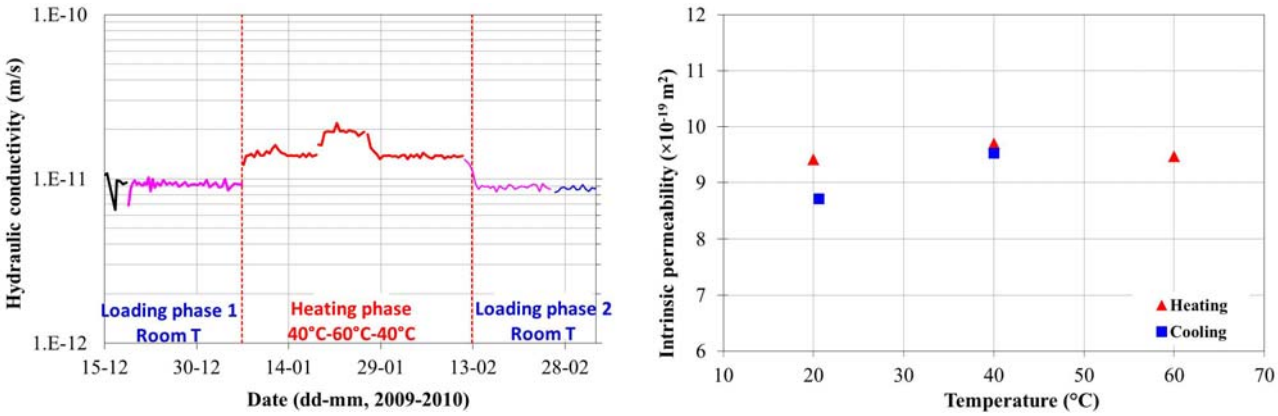
The creation of a damaged zone around the gallery and shaft is inevitable during the construction of repository. The formation of the fractures and the subsequent sealing processes, as well as their influences on the clay permeability at ambient temperature, have been well characterized and quantified in EU project SELFRAC [7]. The in-situ observation that the radial extent of the interconnected fracture zone around connecting gallery of HADES was reduced from about 1 m to less than 60 cm in the first two years after excavation illustrates the good and quick self-sealing capacity of the Boom Clay, even without swelling EBS. The recovery of permeability to the undisturbed value in OPA and COX is slower than in the Boom Clay, but has been shown to accelerate with the confining pressure [7].

Throughout the TIMODAZ project, more evidences on the self-sealing in clay at ambient temperature were collected. For instance, the permeability of a fractured COX sample decreases by four orders in magnitude during the process of hydration in the large-scale hollow cylinder test [5]. In the permeameter tests on Boom Clay sample with a central fracture, the density variation around the central fractures cannot be distinguished from the μCT image after the sample stayed in the cells for 4~6 days without any hydration. The hydraulic conductivity recovers nearly to the intact value [5].

2.2.2 No significant negative thermal impacts on permeability

No significant enhancement of the permeability after thermal loading on three types of clays has been observed in nearly all the laboratory tests involved in the TIMODAZ project, except a significant increase in intrinsic permeability (k_{in}) was observed increasing from 1×10^{-19} m² to 2×10^{-16} m² in one deviatoric drained shearing test on Boom Clay by UJF (BCTIMODAZ03). This notable exception was caused by the reopening of the pre-existing cracks under extremely low mean stress level (*p'*=0.3 MPa). In the repository system, with the recovery of the stress state in the Boom Clay due to creep and convergence of massive, or with the swelling EBS for OPA, such a low mean stress level within the host clay is extremely unlikely.

In isostatic tests on BC and OPA, hydraulic conductivity measured increases slightly during heating, and recover to its initial value after cooling. Also in these tests, the quasi-constant intrinsic permeability indicates that the enhanced hydraulic conductivity during heating is mainly due to the decrease of the liquid viscosity, thus it is reversible with temperature [5]. This reversibility of hydraulic conductivity with temperature was also observed by other laboratory tests within the TIMODAZ project (ENPC, etc.). Figure 13 presents an isostatic test result on Boom Clay. The hydraulic conductivity of a clay samples with an artificial axial hole under the constant confining pressure increases when heating from 40°C to 60°C and recovers after cooling (Figure 13(a)). During the heating-cooling cycle, the intrinsic permeability remains quasi-constant (Figure 13(b)).



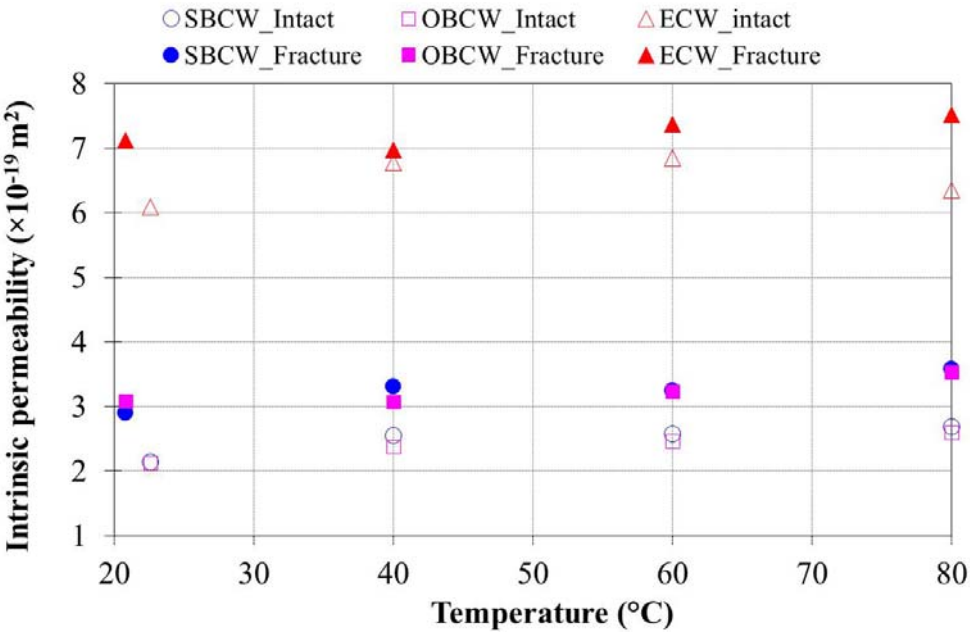
(a) (b)

Figure 13: Variation (a) of hydraulic conductivity with time (b) intrinsic permeability with temperature under the same pressure conditions for Boom Clay in isostatic test (by SCK·CEN)

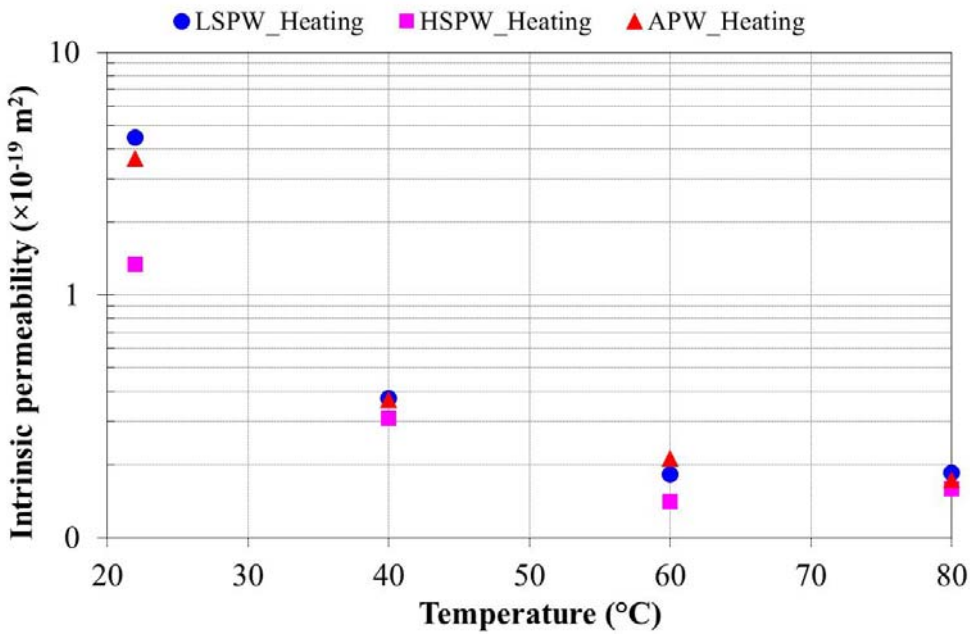
In permeameter test with a rigid cell, the sealing of the central artificial fracture in BC specimens has almost finished 4~6 days after making fractures with samples staying inside the cell. The hydraulic conductivity recovers nearly to the intact value before the heating starts. During the following heating phase, Intrinsic permeability of the BC for both intact samples and samples with artificial fractures was shown to remain constant during the heating phase (Figure 14 (a)),

which suggests that the pore structure of clay is not affected by the temperature and the sealed crack does not reopen during heating [5].

In permeameter test for OPA specimens with central artificial fractures, the hydraulic conductivity started from a value of two orders of magnitude higher than the intact value. In contrast to the Boom Clay, the effect of a temperature increase in decreasing intrinsic permeability is evident in permeameter test when no volume expansion is allowed (Figure 14 (b)) [5]. The same phenomenon was also observed in MONT TERRI in-situ SE-H heater test [3], where the intrinsic permeability shows a continuous decrease by a factor of about 4 when heating from 15.1°C to 65.3 °C. This may be due to the extremely compact structure of OPA. The thermal expansion and swelling of clay particles make the pore space decrease so much that the decrease of liquid viscosity cannot counteract the effect of the decrease of pore space.



(a) Boom Clay (SBCW for synthetic BC water,OBCW for oxidized BC water and ECW for evolved cement water)



(b) OPA (LSPW for low salinity pearson water, HSPW for high salinity pearson water and APW for alkaline pearson water)

Figure 14: Variations of intrinsic permeability with temperature for BC (above) and OPA (below) in permeameter test with fixed volume (by SCK·CEN).

Furthermore, the composition of the porewater, which spans over a range of likely chemical conditions that are representative of the near field of a repository, has no much influence on permeability for BC and OPA [5]. The quasi-constant intrinsic permeability (BC) or even decrease of intrinsic permeability (OPA) at elevated temperature for both intact and damaged clay samples give sufficient phenomenological proof that there is no negative impact of heating on the micro structure of clay matrix in bulk clay.

The observations that permeability is independent of, or sometimes even lowered by heating, support the idea that the clay around a suitably designed, constructed, operated and closed repository will hold its favourable properties of low permeability and self-sealing capacity. Moreover, the conclusion outlined in the SELFRAC final report [7], that the overall performance of the repository system would not be adversely affected even with unrealistic higher hydraulic conductivity of EDZ because the surrounding low-permeability clay limits the supply of flowing water in the EDZ to transport radionuclides, is still valid after considering the thermal impacts.

2.2.3 No negative thermal impacts on self-sealing capacity of clay

In the TIMODAZ experiments, the swelling clay minerals in Boom Clay and OPA, such as smectite, that are responsible for the self-sealing capacity of the clay, are not significantly affected when in contact with in-situ pore water as well as geochemically disturbed pore waters at 90 °C during one year batch experiments [12]. This is also reflected in the stable cation exchange capacity and surface area parameters over the whole duration of the experiment. The shrinkage and swelling tests done by GRS shows that COX still has a significant swelling potential with free expansion up to 12% after being exposed to 120 °C [5].

In permeameter tests, the elevated temperature of 80°C was not found to adversely modify the sealing process of the host clay. The same phenomenon as in the permeameter test of SELFRAC has been observed at elevated temperatures in the TIMODAZ project, namely that an artificial fracture made in the Boom Clay sample quickly seals and is no longer discernible after the sample dismantling. Clearly, all such tests show that sealing is not hindered and that previously sealed fractures are not reactivated at elevated temperatures or during the subsequent cooling.

Moreover, the technique µCT indeed showed the existence of pre-existing fissures in clay samples before testing. However, the permeability tests carried out independently in various laboratories by using different approaches on initially damaged, cut or sheared sample all provide permeability value close to (BC) or evolving towards (OPA) the initial permeability. This also holds for different pore water chemistry. This is a clear demonstration that fissures that are known to exist thanks to µCT investigation carried out before and after the tests, are not detected when running permeability tests. It is hence a confirmation of the excellent self-sealing behaviour of the three clays presently considered as possible geological barriers [5].

2.2.4 No negative impacts on cation exchange capacity

The equilibrium state of geochemical reactions varies with temperature, as do reaction rates. Elevated temperatures increase the solubility of most solids, decrease the solubility of most gases and increase most reaction rates. The geochemical reactions, consisting of ion exchange and mineral dissolution and precipitation, could have effects on the chemistry of pore water and/or the stability of minerals. Thermal effects on clay minerals and organic materials are most prominent in argillaceous formations. These processes should be evaluated to assess the effects of a temperature increase on the retardation, sorption, pore structure, and matrix diffusion properties of the host rock [13].

The one-year batch experiments on the whole-rock sample of OPA and Boom Clay exposed to 90°C suggest that the clay mineralogical composition is not significantly affected by temperature when in contact with in-situ pore water or geochemically disturbed pore waters representative for various possible chemical conditions around a repository [12]. Precipitation of calcite in Boom Clay is observed as a result of temperature increase. Some retention properties such as cation exchange capacity, total surface area are not negatively affected under the applied conditions within one year of experiment time.

Specific to the Boom Clay, both experiment and modelling [14] indicate that the temperature increase will reduce the pH and enhance the partial pressure of CO_2 gas in the pore water of BC. These are mainly due to the thermal degradation of natural organic matter. The drop in pH and the increase in partial pressure of CO_2 may have potential effects on retention of radionuclides. Their effects are however not experimentally studied in the project.

2.2.5 Conclusion and uncertainties

Test results from the TIMODAZ project show a dual impact of elevated temperatures on clay. On the one hand, in the absence of plastic deformation, the micro structure of clay matrix in bulk clay is not adversely affected by elevated temperatures. In case where thermo-plasticity is

observed, clay particles tend to be more compacted by a net reduction of volume as a result of thermo-plasticity and creep. Under a confining environment as expected in repository conditions, closed fractures always remain closed and open fractures tend to seal. But on the other hand, thermal expansion of pore water and strength decrease at elevated temperatures will probably induce additional damage to the clay. If boundary conditions are such that opening of cracks is not possible, no negative thermal impact on safety relevant properties of clay is therefore expected. In all TIMODAZ experiments, test results are positive and there are no temperature-induced open fractures observed. Numerical simulations of repository configuration and the large-scale heater test, PRACLAY in the HADES URF, are expected to provide more insights on this conclusion at the repository scale.

In TIMODAZ, no mineralogy changes due directly to the temperature increase are observed in one year experiment. This means that the original self-sealing and the retention capacities of the studied clays will unlikely be affected negatively by a temperature increase itself. But uncertainties remain, mainly due to the coupling of the temperature increase with other geochemical perturbations at long time scale not studied within the TIMODAZ project. The possible use of cementitious material in the gallery imposes an alkaline perturbation to clay in the near field. Whether the combined effects of temperature and the alkaline perturbation would change the THM behaviour as well as sealing/swelling capacity of clay in a significant way still remains somewhat uncertain [12]. The effect of thermal degradation of natural organic matter on Boom Clay geochemistry is demonstrated but its impact on radionuclides migration is also poorly known.

2.3 Predictive capability of modelling

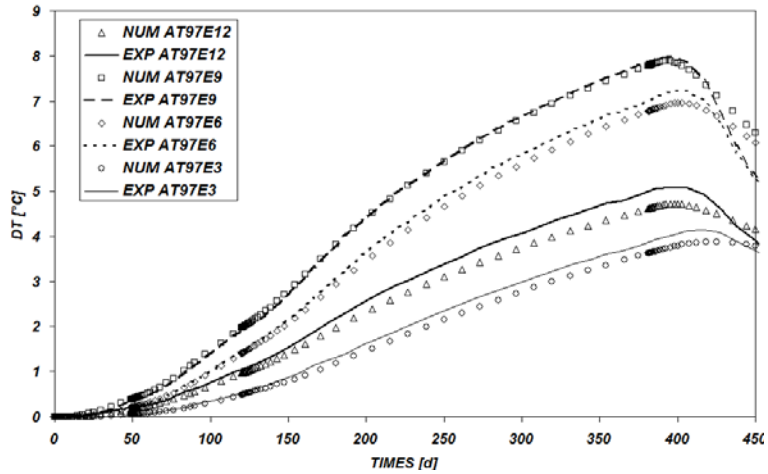
The experimental works performed in the TIMODAZ project investigate various aspects of the interacting processes occurring within the clay around a disposal system for heat-emitting radioactive waste during the thermal transient. Sound characterization of the clay behaviour under these evolving conditions and the supporting modelling work for the interpretation of the experimental results enable a better understanding of the processes that are relevant to the long-term safety of the repository. Furthermore, as the thermal transient is expected to span several centuries, the development and calibration of phenomenology-based models are essential steps towards meeting the safety case requirement of adequate understanding of the long-term evolution at the scale of a repository. The modelling works carried out in the TIMODAZ project aims at improving the predictive capability of models describing the relevant processes including THM couplings and to obtain a better characterization of these processes through validation of the physical models and their parameters.

Extensive benchmarking exercises have been carried out in the TIMODAZ project. Comparisons of numerical results among different teams using different numerical tools have shown that the majority of participants obtain similar results in all benchmark exercises. This not only provides evidence for the verification of these numerical tools in solving THM coupled problems, but also demonstrates that the modellers are applying these different tools in a similar, arguably proper way.

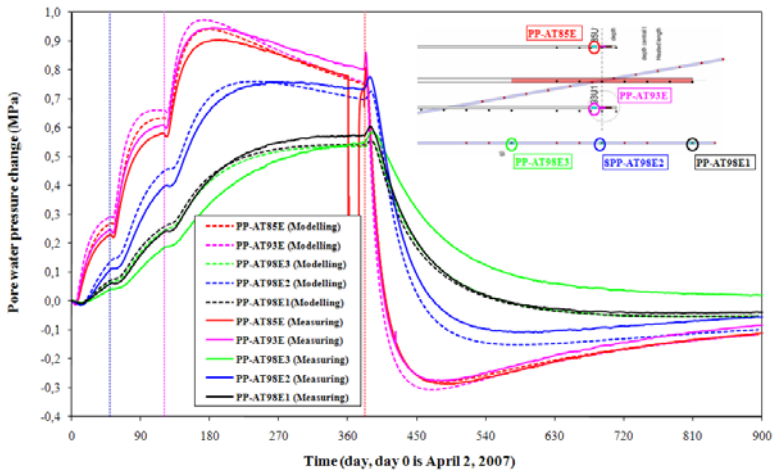
HM perturbation is believed to be reasonably well understood and can be realistically reproduced for the excavation and ventilation phases [7] [15] [16]. In TIMODAZ, numerical modelling for HM disturbances within host clay induced by excavation of the PRACLAY gallery suggests that

the initial stress anisotropy is a key factor to reproduce the anisotropic convergence around the gallery and the observation that the water pressure decreases above or below the gallery while it increases to the right and left of the gallery.

Benchmarking campaigns for the ATLAS III heater test show that the essential features of the THM responses during the thermal transient can be captured, especially the temperature evolution can be reproduced fairly well (Figure 15(a)). Concerning the evolution of the pore water pressure in the surrounding clay induced by the heater, variation pattern in the 3D modelling is quite similar to the experimental data. However the numerical results underestimate the measurements [10]. The discrepancy can be minimized by increasing the elastic modulus which could be justified by the non-linear behaviour of clay [17]. Figure 15(b) shows a satisfactory correspondence between modelling results and measurements for pore water pressure by doubling the Young's modulus [18].



(a)



(b)

Figure 15: Comparison between numerical simulations and measurements of (a) temperature at sensor AT97E (b) excess pore water pressure (parametric sensibility analysis by EURIDICE)

The consideration of in situ stress anisotropy and/or structural anisotropic properties (elastic modulus, thermal conductivity, permeability, etc.) improves the simulation results significantly. Considering the initial stress anisotropy in PRACLAY simulations results in elliptic hydraulic equipotential patterns around the gallery, which are consistent with the in-situ observations. Transverse anisotropy of thermal conductivity in the host clay is demonstrated in both the ATLAS III and SE-H heater tests [3]. Some specific features exhibited in the ATLAS III heater test, i.e. the reversed variation of the pore water pressure for a short time at the beginning of each power change (Figure 11), can only be reproduced by including cross-anisotropic elasticity. It has also been found that the mechanical anisotropy is the reason of the apparent anisotropic convergence around the central hole in the medium-scale hollow-cylinder tests.

The comparisons among simulation results from 2D plane strain, 2D axisymmetric and 3D modelling for the large-scale PRACLAY test provide knowledge on how to make a balance between the model idealization and the precise solutions [10]. It is obvious that the 3D model provides the most accurate results, but it consumes the most computing resources. More often, technical difficulties force the modeller to make a compromise between the mesh quality and computing speed. The 2D plane strain model allows taking into account the anisotropic aspects, but is not able to consider the heat/water transfer along the axial direction of gallery. It gives the similar results as 3D model for a short term analysis when anisotropy plays a much more important role than mass transfer along the gallery. On the contrary, the 2D axisymmetric model offers opportunity to model details all along the axial direction, but does not include anisotropic aspects in the simulation. In the long-term simulations when the effect of anisotropy is not as important as just after excavation, 2D axisymmetric model could give comparable results to 3D model. The idealization of a large-scale in-situ experiment should be carefully determined based on the objective.

Several constitutive models with emphasis on strain/damage localization have been attempted in the simulation of the medium-scale hollow-cylinder tests. A second gradient model was added to the strain cohesion softening model by UJF to simulate the evolution of the strain localization around the inner part of the sample. The embedded fracture model (permeability-strain coupling model) adopted by ULG allows the reproduction of the drastic increase of the permeability of the damaged sample, while the porosity-dependent relationship (Kozeny's model) can not (Figure 16). In order to quantify the permeability decrease of EDZ with the dilatometer load observed in SELFRAC dilatometer test, a model was established by ULG which links the permeability tensor to tensile strain of cracks (crack aperture) and was proved to be able to catch the main HM processes occurring within the EDZ. Comparing with conventional continuum mechanical methods, these advanced models shed light on the future predictions of the evolution of the extent of EDZ as well as the permeability of EDZ. With the help of imaging techniques, effective validation of these new numerical models becomes a possibility. Comparing with conventional continuum models, these advanced models shed light on the evolution of DZ structure and the quantification of its properties.

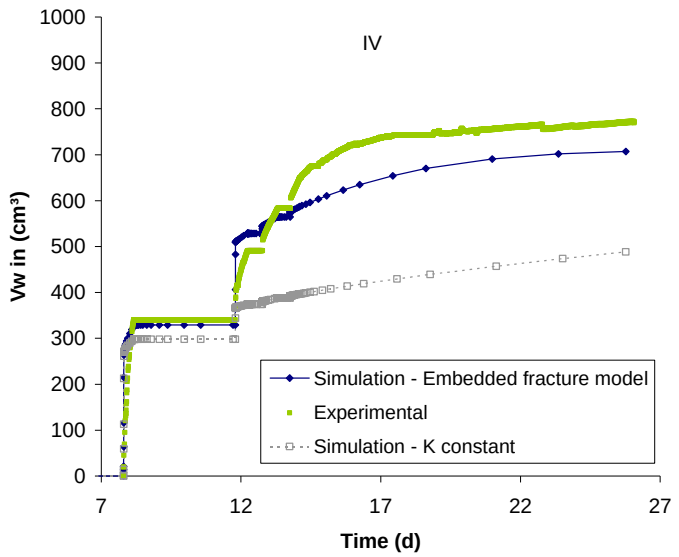


Figure 16: – Comparison of the water volume injected between experimental and numerical results for the large hollow cylinder tests on COX (by ULG).

The phenomenon that the decrease of the permeability of EDZ is a function of the dilatometer load was observed in SELFRAC dilatometer test. In order to reproduce the evolution of permeability within EDZ, a model was established by ULG which links the permeability tensor to tensile strain of cracks (crack aperture) and was proved to be able to qualitatively catch the main HM processes occurring within the EDZ. Future attempts focusing on the mechanism of self-sealing are highlighted to quantify the evolution of properties of EDZ .

In brief, the current status of the modelling work with respect to the formation and evolution of the DZ with time is concluded as:

- Considerable progress **has been made** within the framework of TIMODAZ in adequately capturing key features and processes occurring within the host clay around a repository hosting heat-emitting nuclear waste by models (e.g. HM coupling, anisotropy, THM coupling, thermo-plasticity, damage-dependent permeability, etc.);
- Realistic modelling of the far field perturbations and the extents of the plastic (i.e. how far it goes) seems **within reach**;
- Predictive modelling of the internal structure of the plastic zone and its properties, permeability in particular, **remain elusive**. However, theoretical and numerical development to produce the strain localisation (second gradient model) was significantly improved within the TIMODAZ project, which is a necessary step towards the accurate prediction of the DZ structure.

2.4 Identified uncertainties

Significant progress has been made within the framework of TIMODAZ. Understanding of the THM coupled processes within the DZ has been substantially improved. Most of the results go in

a positive direction and strengthen the assessment basis of the safety of the current repository designs. However, there are still uncertainties about DZ formation and evolution with time under in-situ repository conditions. These uncertainties can be summarized as:

- In-situ sampling inevitably disturbs the clay used in experiments and makes the interpretation of the test results and the model calibration less confident [19].
- Good upscaling prospects from experimental results (section 2.1.4.2) should be complemented with modelling of relevant and large scale in-situ experiments.
- Numerical simulations of the hollow-cylinder tests enable a better understanding of the creation and evolution of the damage zone at the laboratory scale under conditions reasonably analogue to those of a real repository. The developed models are able to reproduce the main processes that occurred in the tests [10]. However, the uncertainties embedded in the tests (pre-existing cracks, influence of membrane and boundary conditions, displacement field assessment method, etc.) make a quantitatively satisfactory reproduction of displacement field rather difficult.
- Advanced stress-strain models incorporating thermal impacts have potential applicability, but the calibration of model parameters of such complex models still needs improvement. Both the relative sparseness and the diversity of the previous test results make the model calibration a big challenge. The main characteristic of the clays tested within the TIMODAZ program is their very low permeability that imposes very long test durations and makes the testing devices very sensitive to leaks and micro leaks. Technical challenges faced by laboratory tests within TIMODAZ project are significant. Consequently, test results obtained within the TIMODAZ time schedule are still limited to validate all developed constitutive models and to calibrate all necessary parameters. With the newly developed apparatus and strictly regulated testing procedures in TIMODAZ, the consistency in the test results have been much improved, which will definitely facilitate the model calibration in the future provided that the test equipment developed with considerable effort for TIMODAZ can be re-used for confirmation purposes.
- The possible use of cementitious material in the gallery imposes an alkaline perturbation to clay in the near field. In combination with high temperature, the reactivity of some types of clay particles (e.g. smectite, organic matter, etc.) may alter the clay in the long-term. Under these circumstances, whether the combined effects of temperature and the alkaline perturbation would change the THM behaviour as well as sealing/swelling capacity of clay in a significant way still remains somewhat uncertain.
- Potential effects of the drop in pH and the increase in partial pressure of CO_2 on retention properties of the Boom Clay due to the degradation of natural organic matter are poorly known.

3. Likely evolution of the dZ/DZ around a repository

A realistic analysis of and the demonstration of an adequate level of understanding of the evolution of the repository system are essential parts of the assessment basis of a nuclear waste repository system. The evolution of the dZ/DZ, an inevitable disturbed/damaged zone within the clay host rock during construction, operation, closure and post-closure of the repository, provides important boundary conditions, on which the long-term safety calculations rest. The state of the dz/DZ and their evolution with time are important to assess the impact on the transport properties. Important parameters such as porosity and the overall effective permeability of the intact and damaged clay are needed for PA. Therefore, an adequate understanding of the dZ/DZ evolution is of paramount concern.

3.1. dz/DZ evolution around a repository in Boom Clay (Belgian design) [20]

During the excavation of the disposal gallery and shaft, a fracture zone is inevitably formed in the first meter of DZ as a result of the mechanical failure caused by stress redistribution. Beyond this fracture zone, a damaged zone (DZ) with enhanced hydraulic conductivity due to effective stress variation is observed around the gallery into the Boom Clay up to 1.25-1.7 times the gallery diameter. The increase in hydraulic conductivity of DZ is limited to one order of magnitude. In-situ test results show that no transmissive interconnected fracture network exists beyond a few centimetres into the Boom Clay. Furthermore the fractures do not play an important role in the enhancement of the hydraulic conductivity in DZ because self-sealing of the fractures was observed to occur in a relatively short time. The permeability of the DZ recovers close to the undisturbed BC value within a few years. In case of instant installation of the concrete lining, convergence can be limited to a few centimetres, thus further development of the fractures is effectively avoided. The consolidation under the hydraulic gradient towards the inner surface of the gallery and the confinig pressure acting on the EDZ imposed by the liner, fasten the sealing process. The ventilation of the repository induces limited desiccation in the clay formation close to the tunnel wall.

Besides the hydro-mechanical disturbances to the Boom Clay during the construction and exploitation phase, there exist localized chemical perturbations to the Boom Clay along the fracture planes. Oxidation of pyrite at the surface of open cracks modifies the chemistry of the pore water. Within the oxidized zone, calcite, which accounts for the buffering capacity of the clay, is prone to be dissolved in the acid water. However, the oxidization affected zone is only limited to the surface of open cracks, the extent of which is about a quarter of the gallery diameter. The acid pore water will not persist very long as the alkaline environment will be dominant with the backfilling of the cementitious material in the gallery. When the pore water reaches the concrete material (backfilling and buffer), the interactions between the Boom Clay and cementitious material will lead to the development of an alkaline plume into the surrounding clay through diffusion. The affected thickness is expected to be less than 2.5 m in the long term.

After the heat-emitting radioactive waste is emplaced in the repository and the repository is closed, the repository system will undergo the most severe transient period on a large spatial scale and in a relatively short period. The emitted heat from radioactive waste induces an

extensive temperature elevated zone in the clay with a peak temperature of more than 70°C within 1-2 decades. The peak temperature, which is restricted by regulation, depends on the properties of the waste, the design of the engineered barriers, and on the spacing between the adjacent disposal galleries. The thermal disturbed zone will extend to the whole thickness of Boom Clay although the max temperature decreases rapidly with distance. As a result of the demonstrated anisotropic thermal conductivity, it is expected that the heat dissipates more easily along the bedding plane.

After the peak temperature, a slow recovery of the temperature to the initial value follows. It is estimated that after 5000 years, the temperature of the host clay will have dropped below 25°C close to the EBS. The laboratory tests within the TIMODAZ project show that there is no significant increase of the permeability of the DZ caused by elevated temperatures. The observed hydraulic conductivity enhancement in clay samples at elevated temperatures is proven to be induced by the variation of the pore water viscosity, thus is reversible and has no negative impact on the permeability of the Boom Clay in the long-term. The enlarged extent with plastic strain due to heat-related reduction of strength, together with other processes including creep and thermal-induced consolidation, will contribute to the sealing of the fractures. After the thermal transient, the stress state and pore water pressure within the Boom Clay will recover slowly to their initial state. This very slow cooling process is expected to have no negative impact on the host clay.

In the time scale of one year, neither clay mineralogy nor cation exchange capacity has been identified to be significantly changed due directly to temperature. This means that safety-relevant properties, such as sorption capacity of clay, will unlikely be affected negatively during the thermal phase.

As soon as oxygen is depleted in the EBS, gas will be produced continuously through anaerobic corrosion of the metals (package of the waste as well as other iron components). Besides this, degradation of organic matters (e.g. kerogen) contained in the Boom Clay produces carbon dioxide. The rate of the corrosion and organic matter degradation is enhanced with high temperature. The gas imposes a risk of creating connected pathways (e.g. fissures or cracks) and localized enhanced water flow within the clay host rock if it cannot be evacuated timely through diffusion.

The post-thermal phase is defined to start when the temperature of the clay around the repository has dropped below 25°C ($\Delta T<10$°C). After the breaching of the overpack expected to occur in the post-thermal phase, radionuclides start to release from the supercontainer and diffuse into the host clay.

PA calculations undertaken to date illustrated that enhanced RN transport through EDZ would not have a significant influence on the dose in the biosphere in the long term, even with very conservative scenarios and assumptions, including the enhancement of the permeability of the EDZ with several orders of magnitude (in combination with an inversion of the hydraulic gradient) and disregarding the barrier functions of EDZ. The self-sealing that is consistently observed further strengthens this conclusion. In the framework of the TIMODAZ project, no significant modification of the safety-relevant properties of Boom Clay, especially self-sealing capacity, has been found at elevated temperatures. On the contrary, several aspects related to thermal disturbance have been found to be beneficial to the safety functions of clay host formations, such as thermal induced creep, plastic deformation and consolidation.

Consequently, the evolution of EDZ through elevated temperatures is not considered a threat for the Boom Clay to fulfil its safety functions in the HLW repository system. However, the

questions related to the evolution of the EDZ in case of gas pressure build-up are not yet answered satisfactorily.

3.2. Damaged zone evolution around a repository of Swiss design in Opalinus Clay

The following discussion considers the scenario of the feasibility study for a High Level Waste / Spent Fuel (HLW/SF) repository in Opalinus Clay at a depth of 650 m below terrain level in North Eastern Switzerland [21][22].

The excavation of access tunnels ramps and shafts as well as the construction of the repository tunnels leads to stress redistributions in the Opalinus Clay that will induce local fracturing in the host rock. A fracture network will be generated in the immediate vicinity of these excavations. The size and connectivity of the network depends on the properties of the excavation i.e. its size, orientation with respect to the in situ stress field, excavation and support techniques.

The excavation damage zone within the host rock is considered for the repository performance along (1) waste the emplacement tunnels, (2) the emplacement tunnel seals, (3) the seals within the access and operation tunnels and (4) the shaft seals. Along the seal sections the temperature effects in the EDZ will be significantly smaller than in the EDZ of the emplacement tunnels close to the heat producing waste canisters. In the following we only consider the emplacement tunnel EDZ.

The waste emplacement tunnels will be excavated subhorizontaly following the centre plane of the host rock layer parallel to the direction of the maximum horizontal stress. This direction maximises the thickness of the geological barrier above and below the emplacement level and ensures minimal stress differences normal to the tunnel section. At a level of 650 m the rock is considered sufficiently strong that the deformation immediately after excavation and during the operational phase is limited (approximately a few % convergence). In case of a deeper emplacement levels operational safety and acceptable convergences will be ensured by a layer of shotcrete and anchors. The stress re-distribution leads to the formation of micro- and macro-scale fractures in the surrounding rock over up to 1 tunnel diameter depending on the emplacement depth. The ventilation during the construction and operation over 1 to 2 years will lead to a desaturation of the inner part of EDZ that will further increase the stiffness of the clay.

After waste emplacement backfilling and closure of the emplacement tunnels the temperatures in the EDZ will rise within a few years from 40°C to a maximum of 80 to 90 °C depending on the thermal properties of the backfill material and the host rock. As the Opalinus Clay has experienced similar temperatures in the geological past mineralogical changes are not to be expected. The heating will lead to an increase of pore pressures in the saturated rock, but this will not increase the size of the EDZ.

During the resaturation period, the progressive strength decrease of the Opalinus Clay and its swelling capacity are expected to result in an effective self-sealing of most of the EDZ, and a gradual further convergence of the tunnels. The convergence will compact the bentonite to a higher density, likely in concert with the resaturation process of the bentonite until the swelling pressure will approximately balance the external stress field and further convergence will come to a halt. The EDZ will gradually further decrease its permeability towards the value of the intact rock.

After full saturation, gas generation will be started by anaerobic corrosion, and subsequent gas migration (especially H_2) will depend on the gas breakthrough pressure both in the bentonite buffer and the surrounding clay host rock, in particular the EDZ. Gas build-up is thus expected to lead to pressures that cause two-phase flow and pathway dilation into the Opalinus Clay host rock. For a corrosion rate of 1 m/a, two-phase flow will be the dominant gas transport process.

Highly alkaline waters will be produced by the cementitious liner materials that would be used if the repository is built at greater depths. The alkaline plume will affect the sorption capacity of the mixed layer clay minerals in the host rock over not more than a few cm from the cement rock contact.

By the time of canister breaching (~10 ka) the EDZ is expected to have decreased its permeability almost back to the value of the undisturbed rock. The temperatures have cooled to a few degrees above initial conditions. The far field rock stress is balanced by the swelling pressure of the bentonite and the fractures in the EDZ are loaded with normal stresses. Self-sealing will occur over a few thousand years. With respect to nuclide migration the impact of THM effects in the EDZ is spatially and temporally very limited. Some uncertainty remains with respect to the impact of the ongoing gas migration on the transport of nuclides.

In case repository induced effects are considered to be not in an acceptable range the design of the repository can be modified in order to mitigate these effects. For example the spacing of the repository tunnels can be increased to reduce the peak temperature in the rock; additionally the excavation damage along repository tunnels or access excavations can be disconnected by the construction of seal sections. Hence, any negative effects on the barrier function of the geological barrier can compensated by design alternatives.

3.3. COX for French design

As in all disposal systems for radioactive wastes the evolution of the envisaged French repository in Callovo-Oxfordian clay depends on the geometry and characteristics of the repository itself and those of the surrounding clay, as well as the mutual influences.

The evolution of the French repository design has been studied extensively in the “Dossier 2005 Argile” [8]. Andra adopted a methodology of the break-down into subsequent states of the repository evolution in time and space. The foreseen evolution of the repository is for a major part based on the observations and the results from experiments carried out at a real site, viz. the Meuse / Haute-Marne site where the underground research laboratory is located.

The identified THMCR phenomena have their own time characteristics, which determine the successive, distinctive states of the disposal system. An example of the evolution of the HLW-modules of the French repository is depicted in Figure 17, showing the chronological evolution of the THMCR processes during the post-closure period. These processes have been discussed extensively in [23] and will not be repeated here. The focus in the present report is on the evolution of the EDZ as outlined in the “Dossier 2005 Argile”, and important findings within TIMODAZ.

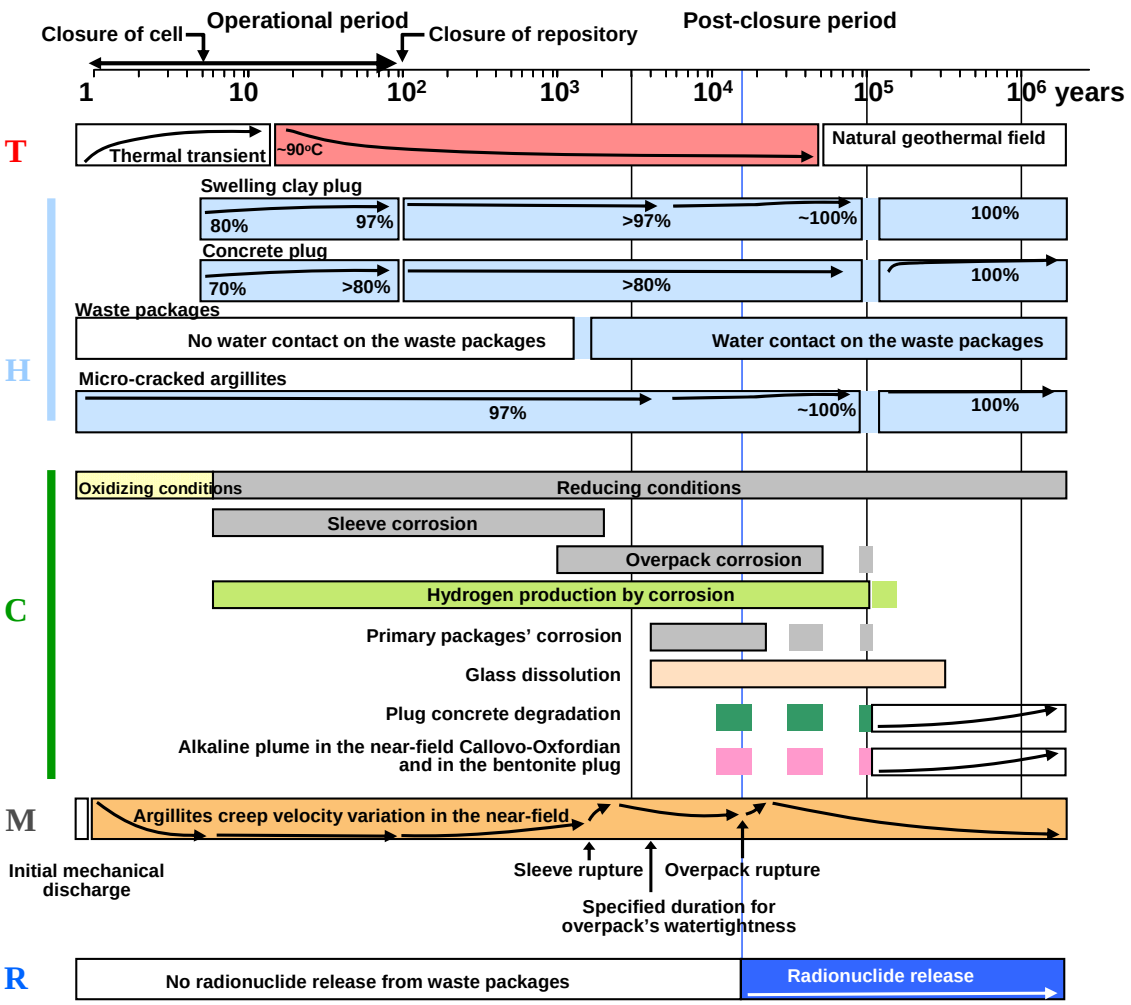


Figure 17: High-level Long-lived Vitrified Waste Modules – Chronological evolution of the THMCR processes during the post-closure period [8]

The damaged zone (DZ) is initiated during the repository construction. In the French "Dossier 2005 Argile" study [8], several forms of damage induced by excavation are distinguished (see Figure 18). Excavating structures redistributes the stresses and deformations in the argillites, leading to the formation of a damaged zone (EDZ) in the rock in the immediate vicinity of the structures. This initial damaged zone is characterised by the appearance of more or less connected fissures, whose density decreases with distance from the wall. Two concentric zones are distinguished that relate to rock deconfinement by excavating: the first one in direct contact with the structures, corresponds to connected fracturing parallel to the axis of the structure (fractured zone) while the other one located at the first one periphery, corresponds to diffuse, hardly connected fissuring (micro-fissured zone).

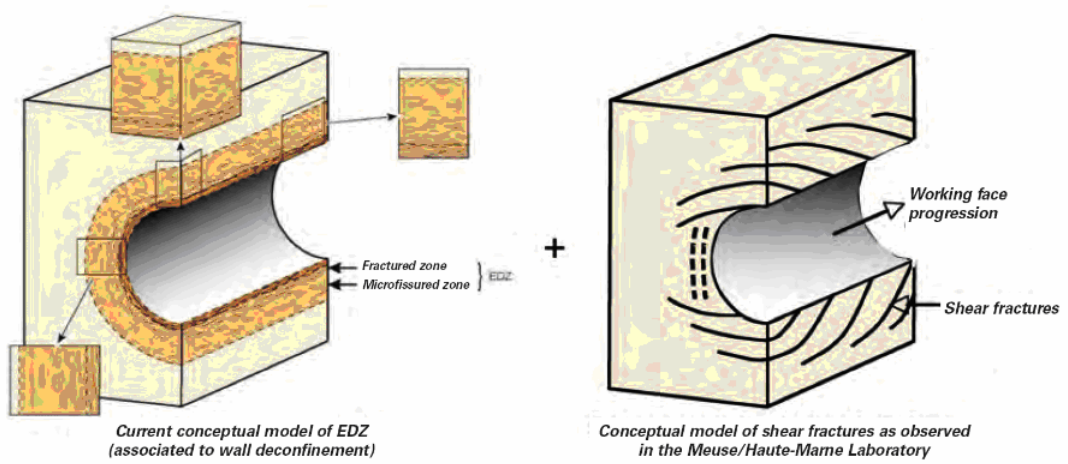


Figure 18:Conceptual diagram of the excavation damaged zone (EDZ) induced by the deconfinement at the excavation wall and conceptual diagram of the shear fractures observed in the Meuse/Haute-Marne underground laboratory[8].

The evolution of the damaged zone as the repository implementation progresses depends on changing conditions that vary from the open-drift period, via the initial closure period, to the entire heating-cooling cycle of the decaying waste. Other factors concern the longer-term issues of chemical reactions and biological activities (cf. Figure 17). The proper evaluation of the effects of the damaged zone on long-term safety is important since its properties may affect the performance of the clay barrier, which provides various safety functions of the repository system.

Rock deconfinement at the edge of the structures may lead to an increase in the argillites fractured zone permeability by a factor of about 10 000 compared to the undisturbed argillites one (5.10^{-14} - 5.10^{-13} m/s). The argillites' permeability in the microfissured zone is increased by a factor of about 100. The permeability of the sheared zones beyond the fractured zone approaches or is less than that of the microfissured zone.

In hydraulic terms, the initial damaged zone observed around the repository structures can thus be considered as two concentric zones:

- the permeability (5.10^{-9} m/s) of the first zone (the fractured zone) is much higher than that of the undisturbed argillites. It extends to less than one meter (about 60 cm according to the model calculations) for a B waste disposal cell and about a few centimeters (less than 5 cm) for a C waste disposal cell;
- the permeability (5.10^{-12} to 5.10^{-11} m/s) of the second zone (the microfissured zone) is less modified when compared to the undisturbed argillites. The extent of this zone is at the most equal to that of the micro-fissured zone, that is less than 6 m for a B waste cell and 20 cm for a C waste cell.

The selection of materials that are compatible with the geological medium from the chemical point of view, their emplacement procedure and the limitation of void spaces in the engineered structures contribute to the overall mechanical stability and avoids the propagation or intensification of the initial damaged zone.

During the partial saturation phase of the repository, in particular around *B waste cells*, drifts and shafts, the argillites become desaturated, and the chemical and mechanical processes such as concrete degradation and argillites creep are slowed down. Desaturation stiffens the argillites and can lead to hydric fissuration over a thickness limited to a few decimeters around the engineered structures. This does however not increase the extent of the initial damaged zone.

Around the *C waste and CU cells*, the temperature increase in the argillites during the first decades after package emplacement in the repository gives rise to thermo-mechanical stresses. Around the periphery of the cells, these stresses can result in a fractured zone with a maximum extent of about 10 centimeters. In the *cell plug*, the minimisation of open spaces and bentonite swelling (effective within a few years to several decades) as well as a less elevated temperature (less than 70°C) do not lead to the development of a fractured zone. Beyond the thermal phase (several thousand years), the return to a natural stress field leads to the re-establishment of the initial damaged zone.

The experimental work on laboratory hollow cylinder tests performed by GRS within the TIMODAZ project [24 , 25] showed that the thermal impact on the fracture closure and permeability is insignificant. In addition to an increasing confining stress, the heat-up of damaged argillites tends to accelerate the sealing behaviour of argillite. These laboratory results indicate that fractures in claystone can be re-sealed within several months under the applied THM conditions.

Upon the subsequent resaturation, after several thousand years, argillite swelling tends to heal the fissures. In the long term, the gradual nature of the mechanical load on the cells (argillite creep), the small void spaces in the engineered structures and the slow chemical degradation of their components do not lead to sudden fracturing of the engineered structures. Their mechanical evolution is gradual over a time scale of several thousand years and does not lead to the propagation or intensification of the damaged zone.

In the long term (over a time scale of several tens of thousands of years), the deferred deformation of the argillites results in a gradual loading of the underground engineered structures. The ground support of these engineered structures, and in the longer term the backfilling materials, take up the stresses. Creep, accompanied by the resaturation of the argillites, gives rise to the closure of any fracturing of the rock and compresses the micro-fracturing of the damaged zone. This gradual healing of the rock tends to re-establish a degree of permeability close to the undisturbed rock one.

4. Treatment of DZ in PA & feedback to design

4.1. Update of D4 report taking into account TIMODAZ results

In the first phase of the TIMODAZ project, the Deliverable D4 - Significance and current handling of the Damaged Zone in Performance Assessment - was compiled to inform specialists in geomechanics and geochemistry and to provide them with an overview of the stakes associated with the DZ in the functioning of the integrated disposal system. In the D4 report, the favourable properties of the host rock used to fulfil the safety functions of the repository are clearly stated as well as the treatment of DZ in previous assessment of long-term radiological consequences. With the guidance of D4, PA analysts and phenomenology specialists kept exchanging information throughout the duration of the TIMODAZ project and reviewing how processes linked with the DZ are translated into models or assumptions within the assessments of repository performance and safety.

With the new knowledge gained in the TIMODAZ project, the critical elements of the D4 report will be updated in the following sections to assess if those favourable properties of clay are still maintained after the heating-cooling cycle.

4.1.1. Are safety-relevant properties of the host rock still maintained after heating-cooling cycling?

The clay host rock contributes dominantly to the **isolation**, **confinement** and **retardation** safety functions of the geological disposal system. In particular, it is important to verify whether the following two sub-functions can be still fulfilled by the clay host rock after suffering whatever disturbances within the repository system:

- Limit the water flow through the system, ensuring that the dominant transport mechanism in the near field is diffusion;
- Retard contaminant migration, referring to processes such as contaminant precipitation and sorption.

The fulfilment of these safety functions is guaranteed by some favourable properties of the clay formations, including the very low permeability of clays, absence of preferential migration pathways, small diffusion coefficient of dissolved solutes through the pores and high sorption capacity of clays. Strong emphasis has been put on these properties for repository designs in clay formations. Other potentially favourable properties of clays such as swelling and sealing capacity can improve the overall robustness of the disposal system. Indeed, the evaluation of the repository safety largely emphasizes the preservation of these favourable clay properties after the thermal phase.

If the EBS behaves as designed in the normal situation (reference scenario), it is the post-thermal state of clay formation (including DZ) after the heating-cooling cycle that determines the

migration behaviour of RNs, and thus the long-term radiological consequences in PA calculations.

- **Very low permeability:** Most of the laboratory tests conducted in TIMODAZ project show that the permeability of both intact clay samples and damaged clay samples are not modified significantly either during heating or after cooling, as long as there are no open fractures. The limited enhancement of the hydraulic conductivity at elevated temperatures is reversible so that the initial value is recovered upon a temperature decrease.

- **Sealing and swelling capacity:** It is demonstrated experimentally that elevated temperatures do not have negative impacts on the sealing and swelling capacity of clay samples. The sealing and swelling capacity of clays rely on the clay mineralogy, especially the content of smectite, which is not found to be modified at elevated temperatures in laboratory conditions for a one year experiment. Instead, test results suggested that thermally induced plasticity and creep have a positive impact on the sealing process.

- **Absence of preferential pathways:** The interconnected fracture pathways parallel to the gallery caused by the excavation are expected to seal in a relatively short period, i.e. within weeks (BC), months (from COX tests) or years. The formation of additional preferential pathways is not expected during the heating-cooling cycle. Whether gas will create new preferential pathways within the clay formation or reopen the already sealed fractures in EDZ still remains uncertain, but is the object of the currently running EC project FORGE.

- **Sorption capacity:** Within the time scale of the experiments carried out within TIMODAZ, there is no evidence of significant modifications of clay mineralogy and cation exchange capacity at 90°C in whatever pertinent pore water composition: e.g. oxidized water, evolved cement water or in-situ pore water. Whether this still holds over longer time-scales is still an open issue. Lasting changes if any of pore water chemistry due to the thermal transient should be assessed, but are beyond the scope of TIMODAZ.

- **Small diffusion coefficient:** The reversibility of the hydraulic conductivity upon subsequent temperature increase and decrease, as demonstrated in the Boom Clay tests, implies that elevated temperatures do not modify the pore structure (intrinsic permeability)[5]. Moreover, in-situ tests and permeameter tests on OPA shows that temperature increases tends to induce a continuous decrease of intrinsic permeability [3,5]. These test observations indicate that the rock factor of the porous medium, and hence the small diffusion coefficient of dissolved solutes through the clay pores will not be negatively modified after the thermal phase when clay is cooled down.

All the relevant test results obtained within the TIMODAZ project suggest that those safety-relevant properties of the clay host rock used to fulfil the safety functions of the repository system are foreseen to be maintained after the heating-cooling cycle. With the current knowledge, it is reasonably believed that the capacity of the repository host rock to perform its intended role as a barrier to contribute to the long-term safety functions of the system is still maintained in spite of the combined effect of EDZ and the thermal flux from the waste. Remaining uncertainties regarding the anticipated gas production due to corrosion are currently under investigation in EC project FORGE. Chemical perturbations in the clay formation were not fully explored in TIMODAZ but results are becoming available in national programmes. Uncertainties related to long time-scales can be addressed by focussing on the modelling efforts.

4.1.2. Is previous treatment of DZ in PA still valid?

Performance assessment is concerned with the potential radiological consequences of the radioactive waste repository for people living in the vicinity of the disposal system. Through rigorous identification of processes and phenomena that can be neglected in the PA analysis, the calculation of RNs transportation within a repository system can be much simplified by adopting the following hypothesis/assumptions. The validity of these hypothesis/assumptions needs to be checked for clay formations experiencing a thermal transient.

- A limited extent of the DZ: The extent of the DZ determines the thickness of effective clay barrier in the PA calculation which is conservatively reduced by the extent of DZ from the geological clay. There are no thermal-induced additional open fractures observed in TIMODAZ. Fractures remain closed and pre-existing fractures are sealed under a confining environment close to in-situ conditions. The DZ is therefore not foreseen to expand after the thermal transient.

- Recovery of the hydraulic conductivity in the DZ: TIMODAZ demonstrats that the thermal transient is not found to have negative impacts on the sealing capacity of the clay. Instead, thermal induced creep and plasticity, swelling and creep of clay are likely beneficial to the sealing of fractures and recovery of the permeability of the DZ to the original state of the clay host rock.
- Diffusion dominant transport in clay formations: In the case of a repository in clay formation, only molecular diffusion through the host formation is considered as RN transport mechanism. This assumption of dominant diffusive transport of RNs is still valid for clay experiencing the thermal transient. As a result that the intrinsic permeability (pore structure) of clay remains constant or even decreases with the increase of the temperature. These test observations indicate that the small diffusion coefficient of dissolved solutes through the clay pores will not be negatively modified after the thermal phase when clay is cooled down.

As the RN transport properties including diffusion and retention (sorption) of RNs of the DZ are not well characterised, the DZ is previously treated in PA calculations by simply reducing the effective thickness of the geological barrier. TIMODAZ indicated that the elevated temperatures do not adversely affect the pore structure of the clay by demonstrating that the intrinsic permeability remains constant or even decreases with the increase of the temperature. Temporary increases of hydraulic conductivity of clay could be explained entirely by the decrease of water viscosity and are therefore reversible with temperature. Moreover, a one year batch experiment at elevated temperatures in TIMODAZ does not show any significant modification of the clay mineralogical composition.

The diffusion and sorption properties of the geological formation around the repository are often considered to be homogeneous and isotropic in PA calculations. Findings from the TIMODAZ project clearly show that clay formations demonstrate strong anisotropic behaviour including mechanical, hydraulic and thermal anisotropies. It has been shown in national programmes [26] and former EC project [27] that diffusion (like heat conduction or permeability) is larger parallel to the bedding planes. The intrinsic, anisotropic properties of the clay formation will make the heat, water and solutes dissipate more easily along the bedding plane. If the layers are sub-horizontal (which is likely for most possible sites), neglecting this effect when evaluating radiological consequences of the repository system is conservative.

Although it is demonstrated in TIMODAZ that a temperature elevation has no negative effect on the sealing of fractures and the recovery of the permeability of the DZ to the original state of the clay host rock, whether the RN transport properties of undisturbed clay can be used for the DZ is still an open issue. The oxidation of the fracture zone that occurred during the operational phase and the later geochemical perturbations might lead to a possible alteration of the geochemical properties of the Boom Clay. However, the thermal impact on the geochemical disturbance zone is beyond the scope of the TIMODAZ project.

Other possible preferential pathways may be formed when the gas produced within the repository system can not be evacuated timely through diffusion. When the increased gas pressure is comparable to the total stress of clay, there is a risk of the formation of new preferential pathway and reopening of the sealed fractures in the DZ. However, the associated induction of water flow is believed to be very small.

4.2. Feedbacks to repository design

4.2.1. Feedback to the Belgian repository design

Vitrified high-level waste and spent fuel release a significant amount of heat even after several decades of cooling in surface facilities. The disposal of heat-emitting radioactive waste in a deep repository located within a clay formation will lead to a considerable heating of the repository materials and the first meters of the host formation. The near field temperature limit for the supercontainer buffer is conservatively set as 100°C in order to preserve the passivation layer of the metallic barriers and to avoid mineral transformations in the concrete. In addition, the constraint of a maximum temperature rise in the far field has a major impact on the disposal design. In the absence of strict regulatory guideline at this point, the temperature at the bottom of the overlying aquifer is constrained to maximum 25°C [28], which corresponds to a temperature increase of 10°C at the top of the Boom Clay [29].

These criteria determine the maximum thermal output per repository footprint area, and the maximum linear thermal load per meter gallery, and hence the minimum distance between two adjacent disposal galleries with a corresponding cooling period. Once the cooling period, gallery pitch, waste package pitch and the gallery diameter are fixed, the detailed design of EBS within the galleries has only an influence on the temperature rise within the EBS itself, but a marginal impact on the temperature rise in the surrounding clay [30].

With the spacing of galleries of 50 m and 120 m for vitrified HLW and SF, respectively, and a cooling period of 60 years, a peak temperature at the contact surface between the gallery lining and the Boom Clay is estimated to be 62°C (ΔT~46°C) after 10 years for vitrified waste and 78°C (ΔT~62°C) after 20 years for spent fuel, considering an isotropic thermal conductivity for the Boom Clay of 1.35 W/(m·K) [31]. Results from the TIMODAZ project show no negative impact on the DZ evolution at an elevated temperature of 90°C in the Boom Clay. The recovery of the hydraulic conductivity in DZ still proceeds all the same with the process of resaturation and the restoration of the in-situ stress state. The safety-relevant properties of the Boom Clay, i.e. low permeability, self-healing capacity, etc., still remain unchanged after the thermal transient.

The anisotropic thermal conductivity of the Boom Clay characterised in the TIMODAZ project gives more input to the temperature evolution field. The (vertical) thermal conductivity in the

direction normal to the bedding plane is estimated from the ATLAS III in-situ test to be around 1.31 W/(m·K), while the horizontal thermal conductivity is around 1.65 W/(m·K). This implies that the above peak temperature based on an isotropic thermal conductivity of 1.35 W/(m·K) seems a little over-estimated because more dissipation of heat will happen in the horizontal direction. Therefore, a better parameterisation of the heat transport process requires feedback to repository lay-out as optimisation.

For very low-permeable clay, the rate of temperature increase is generally more critical than the temperature itself to the potential thermal-induced mechanical effects on the clay surrounding disposal galleries [4].

If the retrievability of radioactive waste from a deep underground repository is required in the future, the stability of the gallery lining under the thermal load needs to be assured. Dramatic increase of the stress at the rock-concrete filling point was observed at the in-situ lining test by CTU in the TIMODAZ project [32]. The large scale PRACLAY test will provide further information on whether this dramatic stress increase has impact on the use of concrete material or compressive material between wedges.

In the present Belgian repository design, the void space in the gallery is backfilled with cementitious material instead of bentonite. Without an EBS actively compressing the clay, the self-sealing capacity of the Boom Clay is still expected to take effect with the evidence that in the permeameter test in TIMODAZ, the artificial fracture in the Boom Clay sample could no longer be distinguished by µCT after a residence time of only 4~6 days with the clay sample in the constant volume cell [5]. Compared to a constant volume cell, clay around the gallery will experience additional confinement due to consolidation and creep of the massive. It was also observed in previous medium-scale hollow cylinder tests that once the fracture is subjected to a normal stress close to the in situ stress, the permeability measured a few days (about three days) after fracturing is found to be hardly different from that measured on the virgin sample [6]. Although the confining pressure will accelerate the process of fracture sealing, the natural closing tendency of fissures and fractures is also related to the clay mineralogy. However, tests with various pore water composition performed in TIMODAZ suggest that the use of a cementitious backfill will not alter the sealing capacity of the Boom Clay in this respect.

4.2.2. Feedbacks to Swiss repository design

The Swiss design of a geological repository for high level waste foresees a spacing of 40 m between emplacement tunnels. A variable canister pitch of 5 to 8 m in concert with a carefully calculated canister loading will ensure an equally distributed heat load along the tunnel axis. Thermal calculations show that the maximum temperatures reached at the inner surface of the EDZ will be in the range of 80°C. These temperatures will be reached within 10 years and represent a temperature increase of approximately 40°C.

The TIMODAZ project has investigated the impact of temperature on the damaged zone. For this purpose laboratory and in situ experiments have been performed under the influence of temperature. The project has shown that the (1) understanding of the temperature impact is adequate and (2) that the temperature increase in the host rock does not impair the favourable properties of the Opalinus Clay.

In particular, it has been shown that the behaviour of tight clay formations can be measured on a quantitative level over the range of temperatures and temperature gradients that are expected for

the immediate vicinity of a geological repository for high level waste / spent fuel. From these measurements conclusions towards the processes involved can be justified. The measurements show that the favourable characteristics of the Opalinus Clay are not adversely affected by a temperature increase of the range foreseen. Finally the project has shown that the numerical modelling of host clay host rock deformation in the damage zone and the strongly coupled effects of a temperature increase in the intact rock can are a feasible task and support (or is consistent with) the current understanding of the processes involved in the repository induced effects.

In detail the experiments confirm that self sealing is not impeded by an increase in temperature. Even high rates of heating do not damage the rock to a degree that can be detected by changes of the hydraulic properties. On the contrary laboratory and in situ experiments both demonstrate that the intrinsic permeability decreases with increasing temperatures. In the laboratory experiments a distinct fraction of the permeability decrease remains after cooling. This finding in concert with the observation of a thermally induced compaction at the upper end of the temperature range may indicate that self sealing will be to some degree assisted by a thermal plastification in the damaged zone.

The long term high temperature tests performed with Opalinus Clay show no mineralogical changes. This indicates that the sorption and retention of radionuclides in the damaged zone will not be impeded by the heat emitted from the radioactive waste in the first few centuries of the post-closure phase.

The excavation of a borehole and its damaged zone in the Mont Terri rock lab confirms the expected process control on the creation of excavation damage around bedding planes parallel to excavations in Opalinus Clay. This understanding opens the way to improve the design with respect to minimising the impact of a connected fracture network around emplacement tunnels and seals. For example the observed pronounced mechanical anisotropy of the rock leads to a predominance of bedding parallel shear failure in the deformation patterns. Therefore the excavation damage may possibly be mitigated or even reduced by increasing bedding cohesion with the help of the early installation of anchors or similar support systems.

In summary the results from the TIMODAZ project indicate that the heat emitted from the waste packages in a geological repository designed according to the current Swiss reference concept [21][22] does not have detrimental effects on the barrier function of the surrounding Opalinus Clay in the damaged zone. The project augmented the understanding of the role of rock anisotropy in the creation of excavation damage and THM effects. Thus it deepened the understanding of the processes involved in the short-term and long-term evolution of the repository system and thereby increased the confidence in long term safety. By showing that self-sealing is not affected and the temperature induced reduction of permeability prevails the project has illustrated the robustness of the system.

4.2.3. Feedbacks to French repository design

In the context of the Dossier 2005 Argile that stated on the feasibility of the radioactive waste deep geological repository in clay rock (Callovo-Oxfordian formation in the Meuse/Haute Marne site in the East part of Paris Basin, argillites type) [23], the French disposal concept consists of disposal cells (underground drifts), whose design allow the emplacement and the retrievability of waste packages with same conditions. Disposal packages consist of primary waste canisters, as

conditioned by waste producers, supplemented by an container, concrete container for IL-LL Waste and carbon steel over pack for HL Waste (vitrified waste: HA type in new French terminology or C type in old French terminology) according to repository requirements [23]. The design of HA disposal cell introduce a metallic sleeve (lining), holding the HA type disposal packages and facilitating these to be retrieved from the disposal cell with same conditions. The sleeve also contributes to improve the heat transfer from the waste to the surrounding clay host rocks.

The repository is designed so that the temperature in the clay rock is limited to 100°C (90°C for design taking into account uncertainties and variability) for all types of waste, in particular HA type. The repository temperature limits is mainly influenced by the thermal power of the waste at emplacement (depending of duration of interim storage), the spacing between disposal cells, the spacing between disposal packages within the disposal cells, and the thermal properties of the engineered barrier components. Given the limited temperature of 100°C and the short duration of the thermal processes (several hundred to thousand years, at the scale of the million years defined for the safety evaluation of the repository), the limited scale of the thermal loading extent, and of maximum temperatures reached in the various waste type areas of the repository and the surrounding clay rock, the clay host rock' initial properties are poorly affected or only to a small extent. In particular, the mineralogical transformations of argillites are small. Since the temperature increase kinetics is slow (several decades) and the thermal load is homogeneous enough at the scale of the Callovo-Oxfordian formation, thermo-mechanical stresses do not cause damage (fracturing) to the layer at a macroscopic scale.

Due to the gradual closure of the residual spaces between the argillite and the sleeve for HA disposal cell, the sleeve is gradually loaded by the argillites. Thermal loading and expansive corrosion products contribute to the stress applied on the sleeve. In [23], it was estimated that the total radial stress on the sleeve could reach 18 to 25 MPa in a transient phase, then at term will stabilize to about 12 MPa, corresponding to the lithostatic stress at a depth of 500 m. This pressure was assessed to be reached at about 1,000 years in the HA waste disposal cell.

Based on the various data acquired, for PA/SA in the context of [23], the Callovo-Oxfordian formation is represented as a homogenous continuous porous medium. Radionuclides can migrate essentially by diffusion and advection is negligible. The permeability values determined in situ or on cored samples are between 10^{-14} and 10^{-13} m/s. In [23] it was recognized that the structure of the medium may suggest permeability anisotropy and lead to cautiously adopting a value ten times higher for the horizontal permeability. The reference PA/SA calculation performed by ANDRA therefore took into account a vertical permeability value of 5.10^{-14} m/s and a horizontal permeability value of 5.10^{-13} m/s. The influence of temperature on the permeability value was not included in SA calculations, taking into account results of preliminary calculations that indicated neutral of beneficial impact of temperature on advection transport in comparison with diffusion in repository situations. However, temperature was explicitly taken into account in SA calculations (coefficient diffusion function of temperature durind and after thermal phase, transient hydraulic field due to thermal over pore pressure and Soret effect (solute transport by thermal gradient), in particular to treat instantaneous fraction of defected HA over packs. .

Through various indicators, the analyses done in [23] have shown that the three main safety functions "preventing water circulation", "limiting radionuclides release and immobilising them in the repository" and "delaying and attenuating radionuclide migration" were effectively fulfilled by the proposed system. For all situations, even considering that the seals are not

effective (situation defined by effective swelling clay core and defective cut off of EDZ – Self sealing of argilites was not considered in [23]), the water entering the repository is very limited, and no significant water flow occurs via the damaged zone and/or backfill of galleries. Clay host rock pathway remains dominant pathway for radionuclides.

Notwithstanding these positive results, the safety analysis performed in [23] indicated some residual uncertainties and margins for potential progress which will provide useful orientations for additional research developments. For the Dossier 2005 Argile, the adopted design approach was guided by robustness and simplicity (with current technological knowledge), so that design optimisation margins exist. On the other way, safety approach has imposed penalising or conservative representation of some phenomena or components (release model of spent fuel, damaged zone...), so that safety margins also exist and constitute reserves which can be used and provide added confidence in the disposal system pertinence and its ability to achieve effective protection for man and the environment against exposure to radioactive waste effects. In accordance with the Planning Act of 28 June 2006, Andra is entrusted now with the design and implementation of geological disposal for high-level (HL) and intermediate-level long-lived waste (IL-LL) in the Meuse/Haure Marne site. Starting from the Dossier 2005 Argile, since 2006, scientific and technological programs, in particular in Bure URL, were defined and are on going to support the work schedule specified by the Planning Act in order to ensure the commissioning of the facility in 2025, in particular filing the repository licence application by Andra (late 2014) after a public debate (planned in 2013).

5. Conclusions

Following the accomplishments of the SELFRAC project regarding scientific understanding of the formation of excavation damaged zone and the self-sealing process of fractures, significant knowledge has been gained in the TIMODAZ project regarding the subsequent evolution of the damaged zone during the thermal transient in the context of a geological repository in clay host rock for heat-emitting waste.

The present knowledge indicates that an increase in temperature due to the presence of heat-emitting wastes will induce strong and anisotropic THM coupled responses within the clay. The thermal expansion of pore water and the thermal-induced decrease of clay strength pose a risk of additional mechanical damage. However, there is no evidence throughout the TIMODAZ experimental programme showing temperature-induced additional opening of fractures or a significant permeability increase of the DZ. Instead, the thermal-induced plasticity, swelling and creep of clay are likely beneficial to the sealing of fractures and recovery of the permeability of the DZ to the original state of the clay host rock.

In the absence of plastic deformation, TIMODAZ demonstrated the elevated temperatures do not adversely affect the pore structure of the clay by showing that the intrinsic permeability remains constant or even decreases with the increase of temperature. Temporary increases of hydraulic conductivity of clay could be explained entirely by the decrease of water viscosity and are therefore reversible with temperature. In case where thermo-plasticity was observed, thermo-consolidation was most likely to occur resulting in a void ratio and intrinsic permeability decrease.

The anisotropic behaviours demonstrated in the TIMODAZ project confirm the existence of anisotropic properties of clay due to the sedimentary nature of the geological formation. Considering anisotropic properties of clay in the numerical simulations has improved significantly the predictive capability of the numerical models. The anisotropy of thermal conductivity will have an impact on the temperature evolution near the disposal galleries, and should be taken into account in the final design of a geological repository.

In addition, the structural anisotropy of the clay formation makes fluid (water and gas) flow, and solute migrate, preferentially along the sub-horizontal bedding plane, which may result in a reduction of the RN contamination levels in the biosphere.

Together with the experimental programme, modelling efforts in TIMODAZ have shown that key features and processes in the clay around a repository system for heat-emitting waste can be adequately captured. In particular, determining the shape and extent of the mechanical damaged zone seems to be within reach. However, intrinsic experimental uncertainties, such as the initial state of samples and control of hydraulic boundary conditions, combined with the uncertainties with regard to the extrapolation of the test results to the repository scale, still make the prediction of the DZ structure and the accurate quantification of its properties, permeability in particular, elusive. So far, good upscaling prospects, e.g. similar fracture pattern exhibited in medium-scale hollow cylinder test and the full size galleries, have been demonstrated in the TIMODAZ experimental programme. The newly developed apparatus in TIMODAZ start to provide high-quality data and will definitely facilitate model calibration in the future provided that these test equipments are re-used for confirmation purposes. The remaining uncertainties will be addressed in the near future by repository-scale numerical modelling efforts as well as large scale demonstration experiments.

With the current knowledge, it is reasonably believed that the capacity of the repository host rock to perform its intended role as a barrier, and to maintain the long-term safety functions of the system is still preserved in spite of the combined effect of the inevitable EDZ and the thermal output from the waste. All the favourable properties of the clay host rock that guarantee the effectiveness of the safety functions of the repository system are expected to be maintained after the heating-cooling cycle. Those basic assumptions used in PA calculations still remain valid when considering the thermal impact on the evolution of DZ around a radioactive waste repository in clay host rock.

As a consequence, the results of the TIMODAZ project strengthen the SELFRAC conclusion that the (E)DZ should still not be considered as a critical issue for the long term safety of radioactive waste repositories in clay formations after the heating-cooling cycle. The development of EDZs and the subsequent evolution of the DZ in current repository concepts do not challenge the safety of the geological disposal of radioactive waste. Remaining uncertainties, such as long time-scales, chemical perturbations, gas production in the system and, incomplete characterisation of clay anisotropy can be addressed in part by valorising the test equipment and sound procedures developed during the project, focussing the modelling efforts on realistic repository configurations and large scale experiments.

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