EUROPEAN COMMISSION

Community Research

TIMODAZ

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

(Contract Number: FI6W-CT-2007-036449)

FINAL ACTIVITY REPORT

Instrument : STREP

Thematic Priority : Nuclear Energy- management of radioactive waste

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Date of issue of this report : **15/2/11**

Start date of project : 01/10/2006 Duration : 48 Months

Project co-funded by the European Commission under the Sixth Framework Programme Euratom Research and Training Programme on Nuclear Energy (2002-2006)		
Dissemination Level		
PU	Public	PU
RE	restricted to a group specified by the partners of the TIMODAZ project	
CO	confidential, only for partners of the TIMODAZ project	

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Part 1 : Project Execution

1 General scope and objectives of the project

Spent nuclear fuel and long-lived radioactive-waste management is an important environmental issue today. Disposal in deep clay geological formations is one of the promising options to dispose of these wastes. An important item for the long-term safety of underground disposal is the assessment of the damaged zone extent induced both by the excavation process and the thermal impact.

The TIMODAZ project studies the Thermo-Hydro-Mechanical and Chemical (THMC) processes occurring around a repository. It focuses on the study of the combined effect of the EDZ and the thermal impact on the repository host rock. The influence of the temperature increase on the EDZ evolution as well as the possible additional damage created by the thermal load is investigated. The knowledge gained within the TIMODAZ project will allow to assess the significance of the TDZ (Thermal Damaged Zone) in the safety case for disposal in clay host rock and to provide direct feedback to repository design teams.

An important item for the long-term safety of underground disposal is the proper evaluation of the Damaged Zone (DZ) in the clay host rock. The DZ is defined here as the zone of the host rock with Thermo-Hydro-Mechanical and Chemical (THMC) modifications induced by the repository, with major changes in the transport properties of radionuclides. These transport properties are the low permeability of clays, a slow diffusive transport combined with the absence of preferential migration pathways for solutes and some sealing capacity.

The DZ is first initiated during the repository construction. Its behaviour is a dynamic problem, dependent on changing conditions that vary from the open-drift period to the initial closure period and the entire heating-cooling cycle of the decaying waste.

The early THMC disturbances created by the excavation, the operational phase and the thermal load might be the most severe transient that the repository will undergo on a large spatial scale and in a relatively short period of time. Consequently the priorities of the TIMODAZ project have been set on the study of the combined effect of the excavation and the thermal impact on the host rocks around a radioactive waste disposal.

Particular attention is given to determine which conditions and phenomena could lead to irreversible modifications of the clay properties, which directly affect the safety functions of the disposal system. These properties are the water tightness or low permeability of clays, a slow diffusive transport combined with the absence of preferential migration pathways for solutes and sealing capacity. The TIMODAZ project assesses under which conditions these basic properties of clay are altered during a thermal transient phase and to what extent the required basic safety functions of the repository system are affected.

Three types of clay are investigated: the Boom Clay, the reference Belgian host formation, the Opalinus Clay, that of Switzerland and, the Callovo-Oxfordian argilitte (COX), the host formation of France.

The knowledge gained within the TIMODAZ project allows to assess the significance of the TDZ (Thermal Damaged Zone) in the safety case for disposal in clay host rock and to provide direct feedback to repository design teams. To ensure appropriate and continuous linkage between the end-user needs and the priorities of the TIMODAZ project, an end-users group that is active throughout the duration of the project has been constituted.

The project started at 1st oct. 2006 and ended at 30 sept. 2010.

2 Consortium

The research activities covered by TIMODAZ calls for multidisciplinary expertise involving both European radioactive waste management organisations together with the main nuclear research institutes supported by other research institutions, universities, industrial partners and consultancy companies (SME's).
The TIMODAZ consortium is composed of 15 participating organisations representing in total 8 countries: ESV EURIDICE GIE (BE), NAGRA (CH), SCK•CEN (BE), GRS (DE), NRG (NL), CIMNE (ES), EPFL (CH), ULG (BE), UJF (FR), ENPC (FR), CEG-CTU (CZ), ITASCA (FR), ASC (UK), ITC (CH) and SOLEXPERTS (CH).

3 End-users group and its roles within the project

The following end-user group consisting of mainly national agencies for management of radioactive waste has been constituted: ONDRAF/NIRAS, NAGRA, ANDRA, RAWRA, ARAO and RATA.

The end-user group is charged to define the end-user needs and to integrate the research results of the TIMODAZ project in a broader, safety case-oriented context, i.e. performance assessment and repository design studies. The end-users group conducts three reviews of the TIMODAZ project based on the implementation execution plan, the progress reports, the deliverables and the end-users workshop discussions. When necessary, the end-user group may propose reoriention of the research.

The end-user group evaluates the results of the TIMODAZ project, and points out how the achievements could be integrated in the overall safety case for disposal in argillaceous rock.

4 The project structure and Methodology

Starting from WP2-*Data review and priority set-up for end-user*, in the TIMODAZ project, new laboratory experimental equipments and test protocols are conceived to study the temperature effects on the EDZ evolution (including sealing/healing capacity) and potential additional damage induced by heating (work-package 3) and new *In-Situ experiments in* small and large scales (work-package 4) are also designed to contribute to a better understanding of the processes occurring within the clay around a disposal system for heat-emitting waste during the thermal transient phase. All experimental researches are closely linked with the development and testing of sound, phenomenology-based *models* which are essential in meeting the Safety Case requirement of adequate understanding of the long-term evolution (work-package 5). Furthermore, all experimental and modelling developments are situated in the long-term performance assessment contexts, with the constant support of work-package 6 - *Significance of TDZ in Safety Case.* To ensure an appropriate and continuous link between the end-user needs and the priorities of the TIMODAZ project, the end-user group has been constituted. Knowledge management and the dissemination of results are also key elements of the TIMODAZ project. Trainings, workshops and international conferences are managed within WP7-*Training and dissemination*.

The project is broken down in 7 Workpackages as shown in Figure 1.

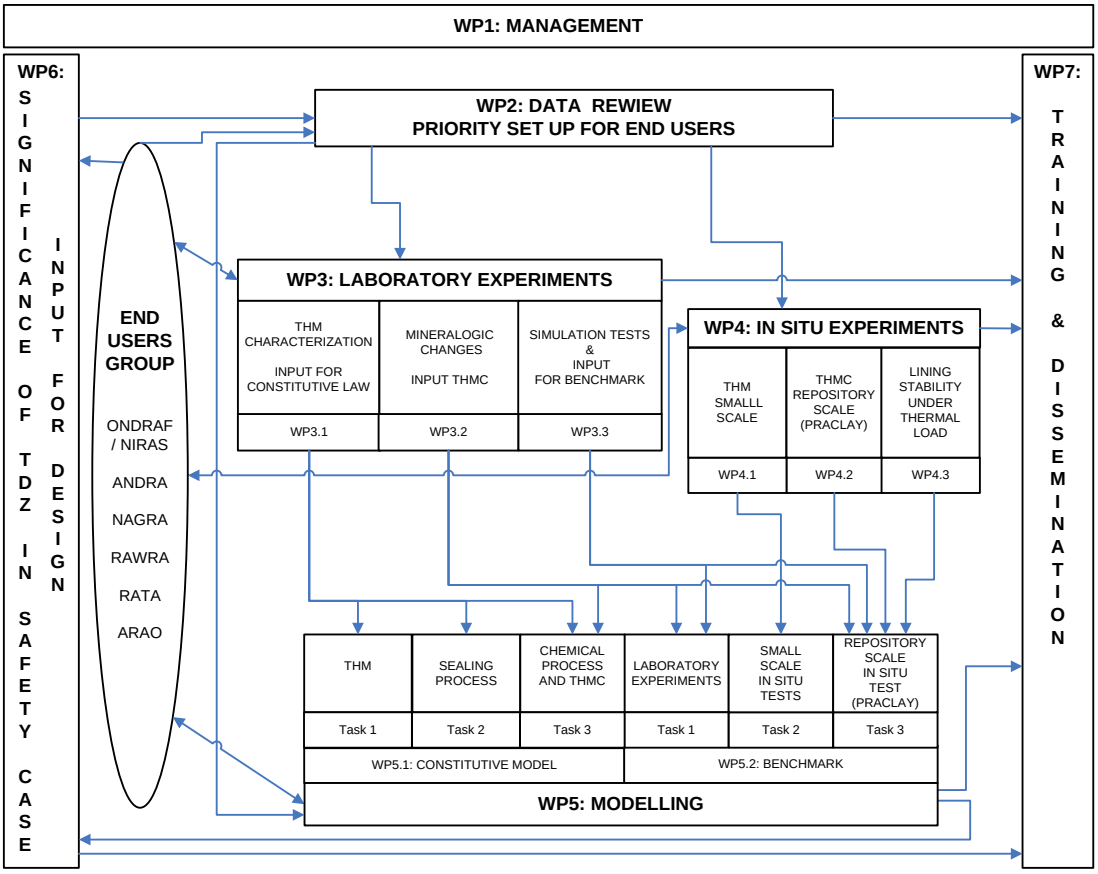


Figure 1 : Structure of the TIMODAZ project

5 TIMODAZ's current relation to the state-of-the-art

In recent years, there have been intense efforts to evaluate the extent and properties of the Excavation Damaged Zone (EDZ), the DZ initiated during the repository construction, involving field, laboratory and theoretical studies (as in the recently terminated EC project SELFRAC). Performance assessment models for different repository designs in different clay formations have demonstrated that even for rather unfavourable EDZ conditions the overall performance of the repository system is not adversely affected and that dose rates remain well below regulatory guidelines.

The influence of the temperature on the clay host rock has also been studied in previous research projects. The THM characterization was mainly performed on samples in surface laboratory and from small/medium scale in-situ heater tests. At the same time, different THM models and numerical codes were developed to better understand the THM processes. However, the influence of the thermal load generated by the radioactive waste on the performance of the disposal system has only been studied at a limited scale of time and space compared to a real repository. This aspect is particularly important since the early transient THM (Thermo-Hydro-Mechanical) perturbation might be the most severe impact that the repository system will undergo on a large spatial scale and in a relatively short period of time after the disposal of the waste. Assessing the consequence of the thermal transient on the performance of the disposal system is the main objective of the proposed TIMODAZ project. Even the full THMC (Thermo-Hydro-Mechanical-Chemical) coupling aspects are studied; the effect of the temperature on the chemistry is investigated in a more limited extent. The TIMODAZ project focuses on the significance of THM processes in the context of the safety case, especially the combined effect of the EDZ and the thermal impact on the host rocks around a radioactive waste disposal. The influence of the temperature increase on the EDZ evolution as well as the possible additional damage created by the thermal load is

investigated.

6 Summary of key activities and achievements

6.1 WP1 - Management

The overall objective of this work-package is to manage the project effectively to ensure the integration of the results within the Safety Case and the set-up of recommendations for repository design. Other tasks of management consist in the stimulation of strong co-operation within the TIMODAZ consortium and information flow with the end-user.

This workpackage consists in the technical, administrative and financial management as well as the co-ordination and administration at all levels between the parties and the EC, including communication.

6.1.1 Coordination Meetings

During the whole duration of the project, 1 kick-off meeting, 9 coordination meetings, 6 Governing Boards meetings, 3 end-user workshops were organised. An exchange meeting with partners of another EC project THERESA and an international conference/workshop on "Impact of Thermo-Hydro-Mechanical-Chemical (THMC) processes on the safety of underground radioactive waste repositories" jointly organised with EC project THERESA were also successfully held. The later one gathers more than 100 participants from worldwide.

6.1.2 Feed-back from end-users: needs, recommendations and evaluation of the project

The end-user workshops within the TIMODAZ project are intended to enable the definition of end-user needs, to review the project and the deliverables as well as to ensure that the results of the TIMODAZ project are directly relevant to the radioactive waste management programs. If necessary, the end-users can propose a re-organisation of the project (which has to be endorsed by the governing board of TIMODAZ).

Together with Timodaz partners, three end-users workshops were organised during the whole duration of the project which marked the milestones of the project.

<u>The 1st end-users workshop</u>

The first **end-users workshop** was held in 13th of June 2007 in Paris.

The general framework of the project and the specific scientific topics were communicated to the end-user group prior to the workshop. During the first end-user workshop, two due periodic deliverables were presented: "*The state of the art on THMC process* "(D2) and "*Significance and Current Handling of the Damaged Zone in Performance Assessment*" (D4) were presented. The status of activities of each work-package were also presented and discussed.

The end-users were asked to

- Review and give feedback on the deliverables
- Formally approve the currently foreseen programme or to suggest deviations of the work programme,
- Evaluate the applicability of the foreseen project results within a Safety Case.
- Give recommendations to or, if found necessary, reorientation of the project.

Based on the information available, the end-user group gave comments on the deliverables submitted

and agreed with the continuation of the project according to the work programme presented and didn't suggest a reorientation.

Recommendations put forward by the end-users

A summary of the end-user needs were given in the deliverable 3 of the project (*D03/WP2- Summary of end-user needs for the project****).***

Several recommendations were put forward by the end-user group, mainly in order to

- Increase the possible direct use of the final outcome of the TIMODAZ project for a Safety Case.
- Strengthen the interaction between experimentalists, modellers and performance assessors

As a first recommendation, the end-user group proposed to clearly check, in the course of the project, to what extent the processes concerning TDZ are really similar for three types of clay studied (going from plastic clay to indurate clay).

The second recommendation focused on the integration of the three domains of expertise (experimental, modelling and PA) present within the project. A possible way of integration might be achieved by making joint presentations at meetings, conferences and certainly end-users workshops of the project.

A third recommendation is also focused on integration of the different disciplines, but now at the level of the project evolution, in order to make the outcome of the project directly useful for a Safety Case.

Within deliverable 4 (§ 6.10: WP6 - Significance of TDZ in Safety Case and Input for Design), five different questions are put forward that need to be answered from a Safety Case point of view. The end-users appreciated very much the listing of these questions and believed that these might be used as a tool in order to strengthen the collaboration between different partners and different disciplines. Based on these 5 questions, the end-users have given some additional feedback on how the collaboration might be enhanced and lead to useful output for a Safety Case:

Q1: What is the expected evolution of the DZ around a disposal system for heat-emitting waste during the thermal period?

It is indeed one of the major tasks of a Safety Case to clearly describe the expected evolution of the disposal system. From a PA point of view, it is important to have an idea on how the damaged zone looks like at the moment of radionuclide release. Taking into account that, for all concepts (linked to the host rocks) considered in the project, the engineered barriers are such that radionuclides (RN) will only be released after several thousands of years, it is thus most important to inform on the evolution for the next 10 000 years. The end-users suggested that, on the one hand, the modellers to make already now predictions/evaluations of the evolutions for the next 10 000 year and, on the other hand, the experimentalists should try to indicate how their experiments will help in describing this expected evolution.

Q2: What are the main uncertainties about the DZ evolution and how can these uncertainties be dealt with?

Within a Safety Case, it is not only necessary to describe how the system will evolve, but also to describe which uncertainties remain on the described evolution. Consequently, it is suggested to inform on the uncertainties that are identified by the modellers (and others) and on how the experimental work is focused on these uncertainties.
To this end, the uncertainties identified in D2 – *state of the art on THMC* and the uncertainties resulting

from the model exercise proposed above under *Q1*, should be addressed. Once again, the end-users stressed the long term (thousands of years) consideration, as this is the eventual input needed for performance and safety assessment.

Q3: Under which conditions can the favourable clay properties be modified during the thermal period and how much can these properties be affected?

In this respect, the end-users considered that it would be most interesting that the PA assessors can already inform to the modellers and experimentalists on:

- Which properties are the most important ones with respect to safety
- What would be a significant change of these properties.

Q4: Under which conditions do the changes in clay properties become irreversible?

The end-users reminded the partners of the project to be very careful with the term 'irreversible' and asked whether another term can be found or at least to clearly define the meaning of the term 'irreversible' within this context. Without better constraining the meaning of 'irreversible' every evolution might be considered irreversible and on top of that the term might have a rather negative connotation.

Note: this question was reformulated later on by the writers of D4 : Under which conditions do the changes in clay properties become irreversible? i.e. under which conditions will the future properties of the clay differ from the currently observed properties?

Q5: To which extent can temporary or permanent alterations of favourable clay properties really affect individual barriers and the safety functions of the repository, i.e. to which extent are these alterations significant from a PA point of view?

This is of course the eventual question that needs to be answered within a Safety Case. However, to which extent this question can be answered is probably strongly depending on the results that will be obtained during the project and to which extent the aforementioned questions can be answered. In order not to postpone this question to the very last moment of the project, the end-users repeated once more their recommendation to ensure interaction between PA and experimentalists and modellers already during the project. This will certainly help to evaluate in how far this question can be addressed with this project.

The 2nd end-users workshop

According to the recommendation of the end-users formulated after 1st end-user workshop, the 2nd end-users workshop was organised at 22 Jan. 2009 in Grenoble, during which three joint "pheno-PA" presentations were given:

- Topic 1: In-depth understanding; experimental & modelling difficulties associated with localisation
- Topic 2: The DZ as a preferential transport pathway
- Topic 3: What does the thermal transient add to the picture?

The end-user group considered that the project is heading in the right direction. No reorientation is needed.

During the discussion, the end-user highlighted the following points:

- Distributed versus localized damage process. Geometry and spacing of discontinuities.
- The role of anisotropy in bedding and stress field.
- Pre-existing inhomogeneous structure(s) within the clay need to be recorded and taken into account.
- What is the confidence for the upscaling and transfer of the lab and small-scale in situ results to full scale repository concepts

All these points are in line with the main concerns of the Timodaz project.

The 3rd end-users workshop

The 3rd **end-users workshop** was organised at 24 Sep. 2010 in Paris, during which the Timodaz team has presented the main findings of the TIMODAZ project. An intensive discussion between Timodaz team and End-users took place. Following main topics were discussed:

- Are TIMODAZ conclusions valid beyond 100°C?
- Prediction of fracture network of an advancing gallery and usefulness of development of coupled anisotropic 3D THM models and numerical tools for PA
- Reliability of new tools of microvisualization
- Synthesis of current understandings from the TIMODAZ project and further events beyond TIMODAZ

In summary, the end-users agreed that the TIMODAZ project made a lot of progress on the characterization of THM(C) processes in different scales and the development of test equipment. Especially the good interaction between modelers and experimentalists was very much appreciated by the end-users.

6.2 WP2 - Data review and Priority set up for End-user

6.2.1 Objectives of WP2

The objective of this workpackage is to integrate the knowledge acquired in previous European projects and national activities about the THM behaviour of clays (especially Boom Clay, Opalinus Clay and Callovo-Oxordian Clay) and the influence of the temperature on the chemical properties. Within this workpackage, priorities for end-user is set-up, so that researchers understand the specific problems for which their research is targeted. The review work and the definition of the end-user needs allows to optimise the experimental programme and to choose the most appropriate constitutive laws for modelling. The review also includes the existing information and results concerning the acceptable thermal limits that the host rock could sustain during the thermal period

6.2.2 Participants of WP 2

9 participants: EURIDICE, NAGRA, SCK•CEN, GRS, CIMNE, EPFL, ULG, UJF, ENPC.

6.2.3 Key results/achievement/deliverables

A report on the State of the Art on THMC behaviour (Boom clay, Opalinus Clay and Callovo-Oxfordian Clay) was produced during the first period of the project (D02/WP2- Deliverable 2 : state of the art THMC)

The first part of the report points out the main issues related to the thermal impact, which should reflect the viewpoints of end users. The second part is devoted to the state of the art for each investigated clay,

including the main characteristics of each clay, the available THM characterisation (both laboratory and in situ), the related chemical aspects and the current development of the constitutive models. The report provides a discussion, for each studied clay, in order to:

- identify the uncertainty for each clay (uncertainty on the experimentally derived parameters, on the THMC coupling process, on the homogeneity of the clay, modelling boundary condition and initial conditions, etc)
- delineate the most important temperature-dependent material properties
- define the most important coupled processes and parameters
- assess the effect of discrete fractures and fracture connectivity on the effective hydraulic properties, to determine the importance of chemical impact
- derive/evaluate the most appropriate conceptual models and numerical codes as well as to notice the remaining uncertainties on the THM properties of the clays

This report gives a synthesis of the relevant works previously performed on the three investigated clays in surface laboratories and in in-situ facilities. The range of the most important THM parameters, the in-situ observations are presented. The accompanied uncertainty is highlighted and analysed. The modelling results of the selected in-situ tests are included. The capacities, the limitation of the developed/applied models are discussed. The associated future developments on the constitutive models are thus underlined.
It comprises thus a database and a reference document to optimise the testing procedures of the laboratory experiments and the in-situ experiments to be performed in the present project.
The end –user needs was summarised in §6.2. and reported in detail in D03/WP2- Summary of end-user needs for the project.

6.3 WP 3.1 - Laboratory experiments: THM characterization / Input for constitutive laws

6.3.1 Objectives of WP 3.1

The general objective of this sub-workpackage is to perform the tests in laboratory under well controlled temperature/stresses/pore pressure conditions with different well defined loading paths in order to determine the parameters of the Thermo-Hydro-Mechanical constitutive models used for the numerical modelling. More specifically, the thermal effects on the damaged clay and the possible damage induced by the thermal loading itself will be investigated. The tests include the study of the desaturation/resaturation processes at ambient and at different temperatures. Specific attention will be given to the possibility of the creation of an irreversible damage. During the tests, different techniques will be used to evaluate the sealing/healing processes (water/gas permeability measurements, µCT, etc.). Some tests will be complemented with a radionuclide migration test to evaluate any possible relict of preferential migration along the sealed fracture

6.3.2 Participants of WP3.1

6 participants: SCK•CEN, GRS, EPFL, ULG, UJF, ENPC

6.3.3 Key results/achievement/deliverables

Experimental investigation was carried out in the various groups by using specific devices aimed at better understanding the impact of temperature on the damage zone and on the isolation performance of waste isolation systems, as specified in the TIMODAZ project title. The better understanding of the physical phenomena involved and the THM behaviour parameters obtained have been provided to the participants of WP5 devoted on numerical modelling.

The contribution from UJF included the modification of a high pressure triaxial cell in order to apply

thermal loading. Moreover, X-ray computed tomography (CT) was systematically carried out prior to testing and after testing. It appears that X-ray CT provided major added value to the TIMODAZ project. In particular, X-ray CT allowed assessing the presence of pre-existing discontinuities in the specimen and their impact on specimen deformation upon deviator loading.

The main goal for the EPFL was to investigate the rheology of clay rocks in THM conditions focussing on the effect of temperature on the unsaturated behaviour of Boom and Opalinus clays. Two research axes have been investigated, the analysis of the effects of temperature and suction on the mechanical response and the study of the drying behaviour (desaturation process) at different temperatures.

The contribution from ENPC to the project included the conception, fabrication, setting up and use of a new THM hollow cylinder triaxial cell specially designed for the TIMODAZ project for very low permeability samples. The feasibility of this new system has been more difficult than planned with underestimated problems linked to leaks occurring under high temperature and pressure.

Various triaxial experiments were conducted by GRS on the Callovo-Oxfordian claystone (COx) under well controlled conditions which can be expected in underground repositories in clay formations. These include heating the samples up to 150°C to investigate thermal expansion and contraction, pore-water pressure changes, temperature influence on deformation and damage, shrinkage and swelling.

ULg's experimental program focused on the anisotropic elastoviscoplastic behaviour of Boom Clay based on triaxial tests at different loading rates, with creep or relaxation phases on the samples cored in different directions with respect to bedding.

SCK•CEN focused on the investigation of the temperature effect on the seal-sealing capacity of Boom clay and Opalinus clay by means of permeability tests in permeameter and isostatic cell.

Experimental techniques developed and used within Timodaz project

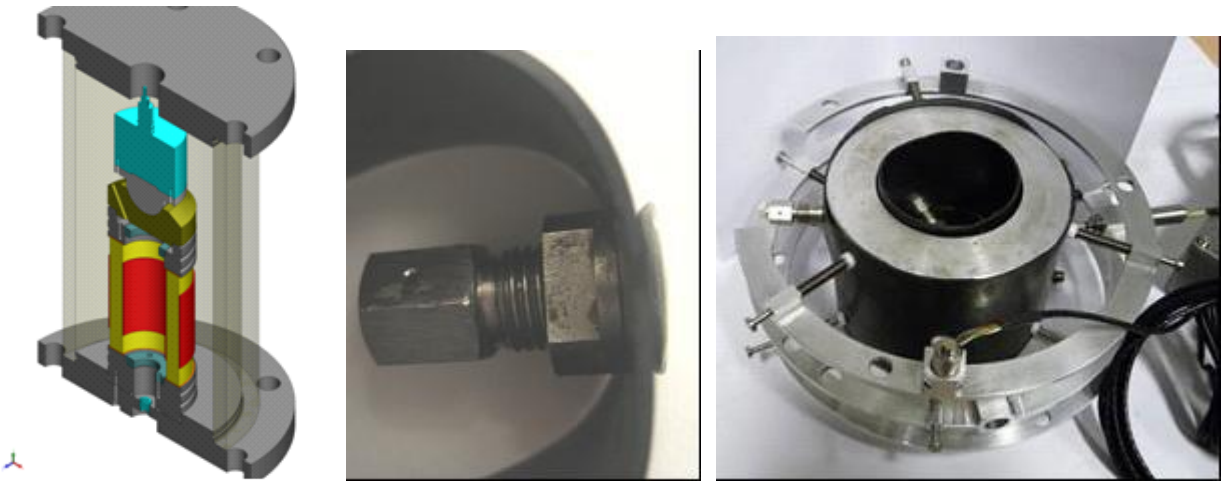
The problem addressed in the project is a complex thermo-hydro-mechanical problem typical of the close field, also accounting for the effects of discontinuities, sealing and partial saturation on fluid transfers. As a consequence, a great variety of experimental techniques not so commonly used in geomechanics when dealing with low permeability clays and argilites have been developed and used.

The experimental challenges faced in the TIMODAZ project to tackle coupled THM phenomena in relation with damage evolution in the EDZ are significant. The very low permeability of the clays investigated also involves quite long testing periods and thus asks specific experimental precautions (both in the shearing and heating phases).

Figure 2 shows the hollow cylinder cell developed at ENPC so as to provide a short drainage length of 10 mm (the half thickness of the hollow cylinder), compared to 38 mm in the case of standard triaxial samples drained on top and bottom. Roughly, the corresponding rate in terms of water transfers (initial saturation, drained nature of the tests) is estimated to be 16 times faster than in the case of a standard 76 mm high triaxial sample, given the diffusion nature of water transfer equation. In particular, the one year period necessary to detect on top a pressure applied to the bottom in some case is reduced to less than one month.

Figure 3 illustrate the sorption bench developed in EPFL to determine the water retention properties at different temperatures.

Figure 4 shows the multi-scale x-ray CT scanner recently acquired at Laboratoire 3S-R (UJF). The system allows for high spatial resolution (in the order of a few microns), which is crucial for imaging fissures and localized damage in Boom Clay and Opalinus Clay.



a) b) c)

Figure 2. a) ENPC new hollow cylinder triaxial TIMODAZ cell; b) Connection to the geotextile; c) local strain measurement with LVDTs

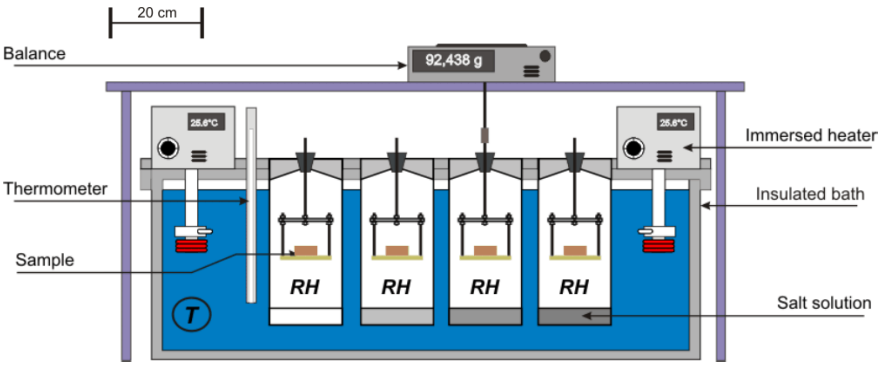


Figure 3 : Experimental layout of the sorption bench for the WRC test (HR stands for Relative Humidity)

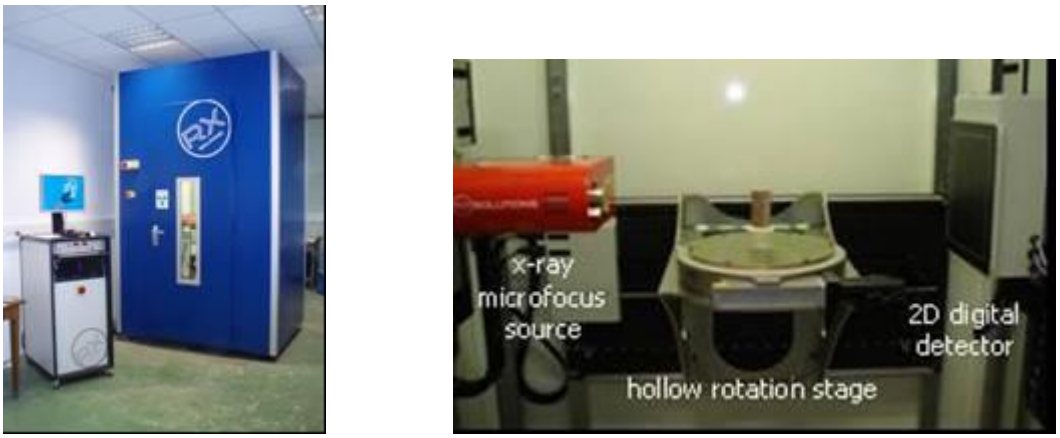
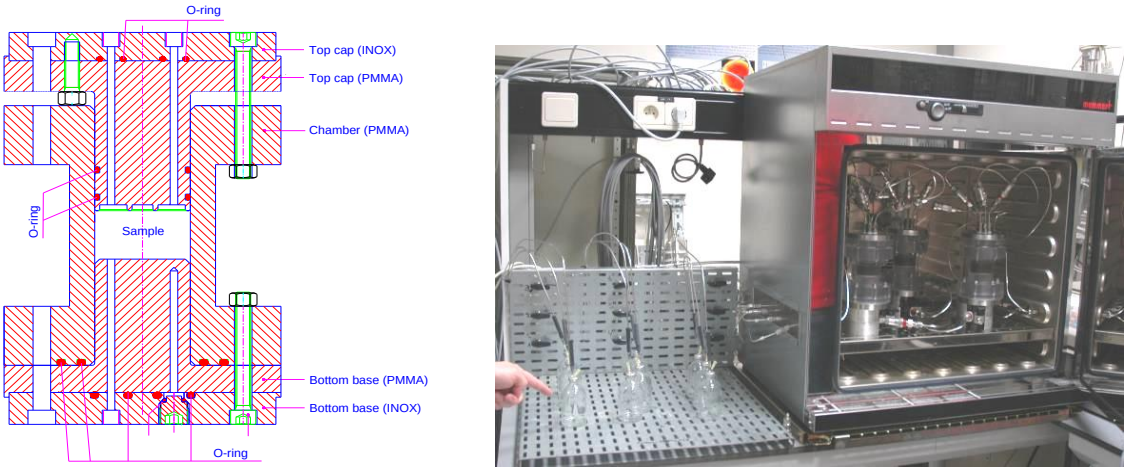


Figure 4 : X-ray CT scanner at Laboratory 3S-R. Overall view of the large cabin (internal dimensions: height 290 cm, width 175 cm, depth 135 cm) and remote computer control (left photograph), and main components of the system (right photograph).

Figure 5 shows the specific designed permeameter cell for permeability tests on fractured samples.



(a) Cell structure (b) Oven, cells, bottles to collect outflow

Figure 5: Cell of permeameter test on Boom clay

Selected results

Detailed testing procedure, lessons learnt from technical problems encountered during the construction/testing, test results and main achievement are given in D05/WP3.1-THM characterisation/input for simulation**.**

At **UJF**, triaxial HTM tests were performed to study the effect of a thermal loading (heating/cooling process) on mechanically damaged clay, *i.e.*, to evaluate the impact of the thermal loading on the process of localisation and/or fracturing.

A complete HTM test includes a total of 10 stages: 1) scan of the specimen (x-ray CT); 2) isotropic consolidation phase (up to p' = 2.3 MPa and u = 2.2 MPa, *i.e.*, in situ mean stress; 3) permeability measurement; 4) deviatoric loading up to "failure"; 5) permeability measurement; 6) thermal loading (heating phase); 7) permeability measurement; 8) thermal loading (cooling phase); 9) permeability measurement; 10) scan of the specimen (x-ray CT); see Figure 6.

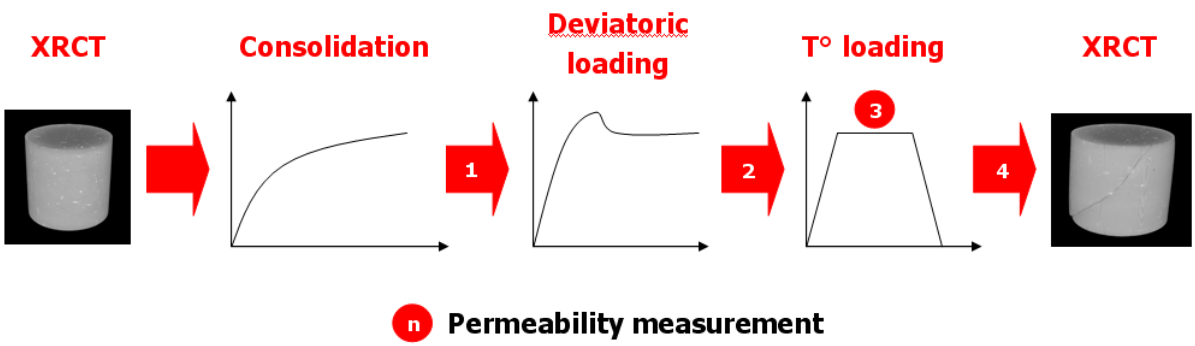


Figure 6. Sequence of stages of a typical test at UJF

For the deviatoric loading, different paths have been followed in the experiments either under "*drained* " or "*undrained* " conditions. The test adopting a mixed-mode control paths (by applying a constant axial strain rate and decreasing in the meantime the cell pressure, an original, non-standard testing procedure) was motivated by the objective of loading the specimen along a stress path mimicking a situation similar to the one resulting from tunnel excavation where the stress deviator increases while the total mean stress decreases. A mixed-mode control is needed in order not to loose control of the test when passing

through a load peak.

Permeability is measured at four stages of a test, at the end of consolidation, after deviatoric loading, after heating and finally after cooling.
The main result from these measurements was that essentially no significant changes of permeability were associated neither to the mechanical nor to the thermal loading for both Boom clay and Opalinus clay.

The systematic use of x-ray CT (prior to testing and after testing) allowed assessing the presence of pre-existing discontinuities in the specimen and their impact on specimen deformation upon deviatoric loading. It should be realized that in ALL tests performed on Boom Clay the deformation eventually localized in one or more shear zones. In some cases, the final shear zones were found to correspond in fact to sliding along pre-existing fissures. For example, this was the case of test BCTimodaz04 (see Figure 7).

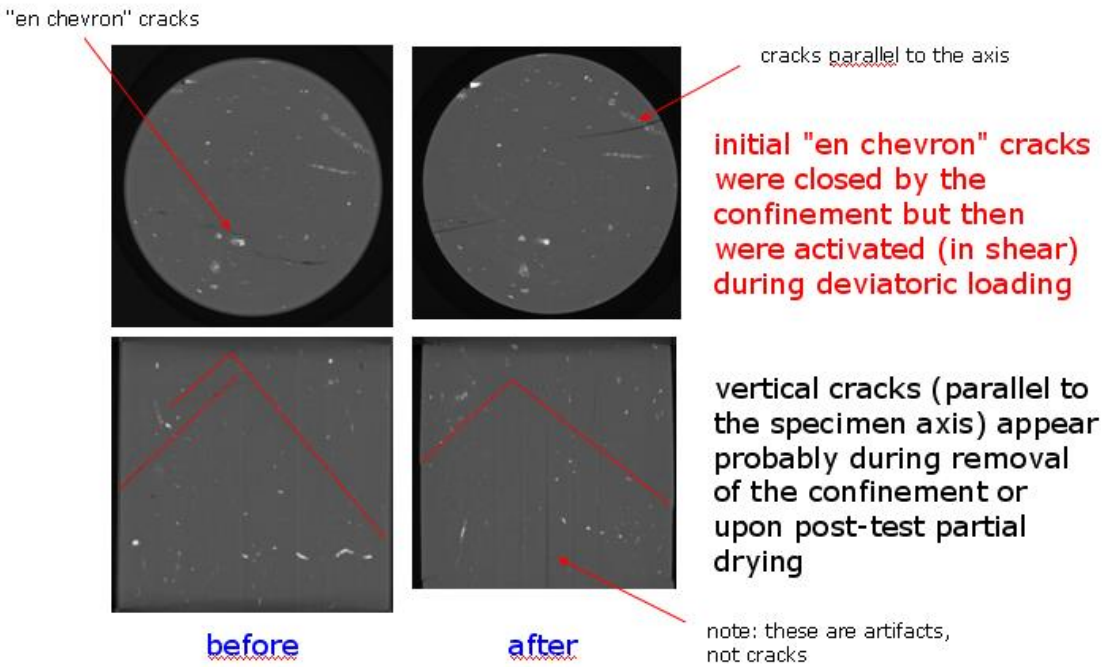


Figure 7. Impact of pre-existing fissures on strain localization upon deviatoric loading (test BCTimodaz04).

At **ENPC**, hollow-cylinder triaxial THM tests were performed on both Boom clay and Opalinus clay under different stress paths and different hydraulic boundary conditions.

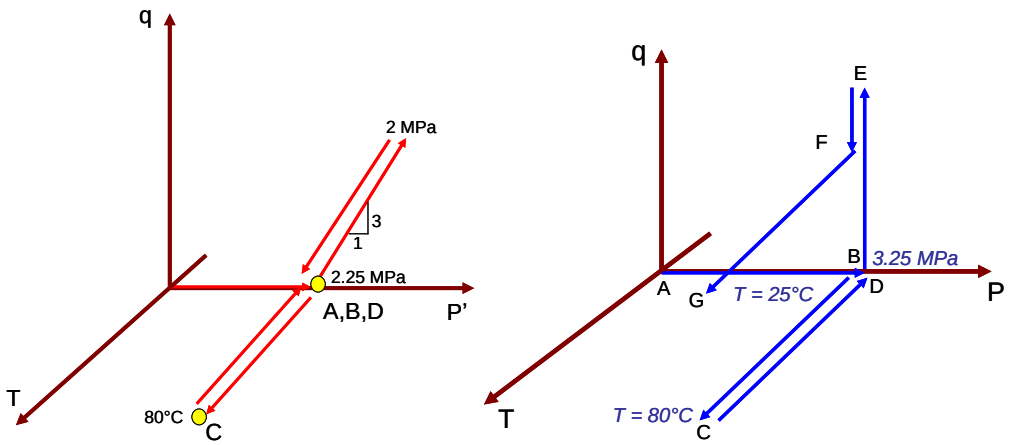
Figure 8 illustrates the THM stress paths followed for 2 tests on Boom clay. All tested samples were saturated under approximately in-situ stress conditions to limit the swelling and better preserve the initial state of the sample. The saturation degree was checked systematically by measuring the Skempton coefficient. Permeability was measured at different stages of the test by using the transient method based on the pore pressure dissipation curves measured by pressure transducers installed at different positions allowing measurement of the anisotropic permeability.

The permeability calculations during test 2 on Boom clay show:

i) A decrease in permeability after shearing (drained) that can be explained by the increase in total mean stress during the shearing phase. There is no apparent effect of the shear plane on pore pressure diffusion and permeability, confirming the good self sealing properties of Boom clay already reported during the SELFRAC project;

ii) The faster dissipation of the pore pressure at 80°C can be explained by the increase of water viscosity, with no significant effect on the intrinsic permeability as already reported by Delage et al. (2000).

iii) Permeability goes back to initial value (point C) after cooling, confirming again the very good sealing properties of Boom clay. the thermal effect on the permeability is reversible.



a) drained shearing, heating under drained b) undrained shearing, heating under undrained

Figure 8. THM stress path : a) 2nd test on Boom clay ; b) 3rd test on Boom clay

The third test on Boom clay demonstrated that the cracks (fractures) can be reactivated under undraind heating condition (thermal failure) by the undrained thermal expansion of water in the crack, provided the crack remains saturated and submitted to fast heating. This might not be always the case in the near field thanks to evaporation and crack drying.

The tests on Opalinus clay provided interesting results bout the thermal plasticity behaviour of this material. Indeed, to the authors' knowledge, there are no data available in the literature about the thermal behaviour of Opalinus clay, unlike in the case of Boom clay.

The results shown in **Figure 9** probably present the first thermal experimental response obtained on Opalinus clay. They evidence a dilating thermal behaviour between 25 and 65°C, followed by a contracting response between 65 and 83°C. When temperature is decreased, the sample exhibits a contraction that is first quite significant (0.2% between 83 and 75°C) and that afterwards follows a slope comparable to that of the first heating dilation (indicated in **Figure 9**). The second heating/cooling cycle exhibits a thermal dilation up to 80°C followed by a contraction when temperature is decreased and an irreversible volumetric strain close to 0.12%. The dilating response under the first heating phase is comparable to that of overconsolidated plastic clays as shown on Boom clay. It corresponds to the thermal dilation of the solid particles. It is interesting to note that 65°C is the maximum temperature supported by Opalinus clay during its geological history. Above this maximum temperature, the sample contracts and its response can be compared to that of a normally consolidated plastic clay. Also, observation of the second heating cycle shows that, once the maximum previously supported temperature is over passed by heating up to 85°C, this dilating-contracting trend no longer appears with a single dilating phase up to 85°C. This behaviour is a typical thermoplastic behaviour, evidencing a thermal hardening. The slope of the cooling phase gives an estimation of thermal drained expansion coefficient of Opalinus clay, equal to 6.4 x 10^{-5}/°C. The permeability measurements before and after shearing on Opalinus clay indicated increasing of permeability after shearing, which evidences a significant effect of undrained shearing and associated shearing induced damage.

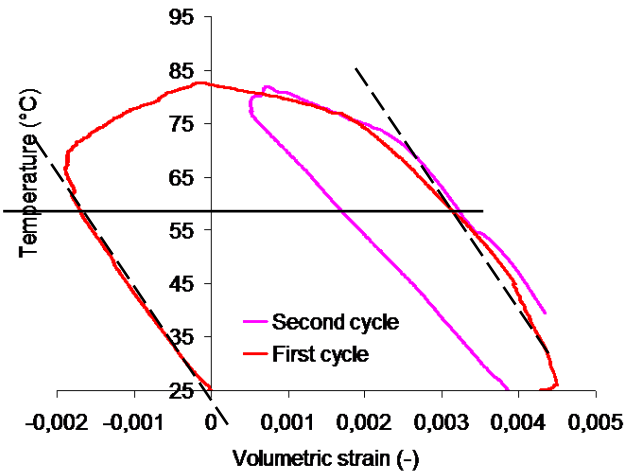


Figure 9 : Drained heating test on Opalinus clay

The permeability tests performed by **SCK•CEN** in both permeameters and isostatic cells at different temperatures indicated the good self-sealing capacity of both Boom clay and Opalinus clay. The temperature has non negative effect on the self-sealing behaviour. For Boom clay, there is a good consistency of the hydraulic conductivities in SBCW (Synthetic Boom Clay Water) and OBCW (oxidized synthetic Boom clay water) geochemical conditions. ECW (evolved cement water) conditions are difficult to interpret because of the swelling of the sample. For Opalinus clay, LSPW (low-saline Pearson water) and HSPW (high-saline Pearson water) can maintain the sealing capacity, while the test with APW (alkaline solution composed of a low-saline Pearson water saturated with calcium hydroxide) seems to indicate incomplete sealing and some reversible damage.

Figure **10** gives the triaxial test results on 4 Boom clay samples cored in different directions and sheared at different rates obtained at **ULg**. The viscose behaviour (load rate dependent responses), the anisotropic mechanical behaviours (core direction dependent responses) were put in evidence.

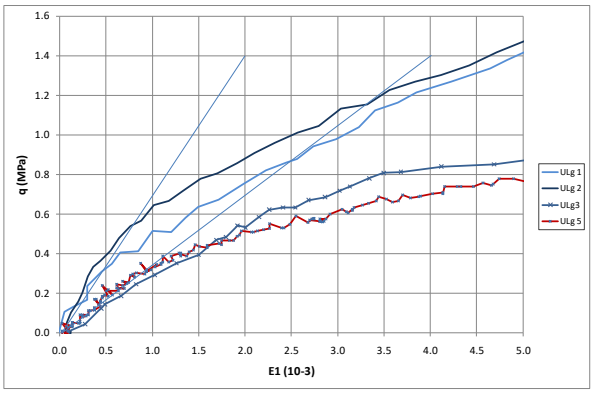


Figure 10 : Stress- strain curves of the tested Boom clay samples (sample 1 & 2 are cored parallel to the bedding; samples 3 & 5 are cored perpendicular. The loading rate is $5*10^{-5}$ MPa/s for samples 1, 2, 3 and $5*10^{-6}$ MPa/s for sample 5.)

The water retention curves at different temperatures for Both Boom clay and Opalinus clay were successfully obtained by **EPFL** (Figure 11).

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Boom clay

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Opalinus clay

Figure 11 : Water retention curves of two studied clays at ambient temperature and at 80°C, in terms of water content; void ratio and degree of saturation (EPFL results)

At **GRS**, various kinds of tests have been conducted on COX samples under well controlled conditions being expected in underground repositories in clay formations. These include heating the samples up to 150°C to investigate thermal expansion and contraction, pore-water pressure changes, temperature influence on deformation and damage, shrinkage and swelling. Significant responses of the clay samples to thermal loading were observed in different conditions, from which the following conclusions can be drawn:

- The thermally-induced pore-water pressure changes were detected by monitoring the back-pressures during heating the highly saturated samples in undrained condition. The pressure values measured by increasing the temperature up to 90°C which is designed for the maximum in the host clay surrounding HLW, stay below the applied confining stresses.
- The thermal expansion of the claystone depends on the water saturation and the hydro-mechanical boundary conditions. In saturated and undrained conditions, the thermal expansion is predominately controlled by the pore water because its thermal expansion coefficient is about two orders of magnitude higher than that of the solid grains. In unsaturated and/or drained conditions, heating causes mobilisation and expulsion of the pore water from the rock, giving rise to pore collapse and thus shrinkage as well as consolidation, depending on the confining stress. The thermally-induced consolidation enhances the stiffness and strength of the claystone.
- Heating and drying up to 120°C generates a limited shrinkage below 1% but no fracturing even in unconfined conditions.
- The claystone, even though previously exposed to high temperatures up to 100 to 120°C and highly desaturated, still exhibits a significant swelling potential with large free expansion up to 12% and high swelling pressure up to 5 MPa during wetting with water vapour.

General conclusions from WP3.1

The program carried out within the WP3.1 Work Package was based on the use of various specific experimental devices aimed at identifying various aspects of the thermo-hydro-mechanical behaviour of three clays and/or claystones used as geological barriers for radioactive waste disposal at great depth, namely Boom clay (BC, Belgium), Opalinus clay (OPA, Switzerland) and Callovo-Oxfordian clay (COx, France).

The characterisation of some multiphase features of the clays included the water retention properties at various temperatures and confirmed that an elevation of temperature decreased the ability of the clays to retain water. Compression tests at various temperatures carried out on Opalinus Claystone also showed higher compressibility at elevated temperature (80°C).

The main characteristic of the clay tested in the program is their very low permeability that imposes very long test durations and makes the testing devices very sensitive to leaks and micro leaks. For this reason, various new experimental developments appeared to be much longer than initially planned. An added technical difficulty is the negative effect of elevated temperature on water tightness. Other difficulties that have been commented in the report are linked to the initial state of the samples that are somewhat desaturated, at least in the case of the claystones (OPA and COx). Some questions also arose about the homogeneity of the pore pressure field inside the specimens and also about the exact meaning of what is called “drained conditions”. In this regard, the development of new devices with small drainage length appeared promising thanks to the significantly higher dissipation rates permitted.

Although it was not initially planned, the project has significantly beneficiated of the recent developments of a technique specifically devoted to cracks and discontinuities, namely the microcomputerised X Ray tomography (X-Ray µCT), used in three groups in relation with the others. In other words, the impressive recent worldwide development of this technique appeared to be exactly coordinated in time with the project progress, quite a positive point. This technique indeed showed the importance of pre-existing fissures that will be further commented later. The comparison of samples before and after THM testing (a methodology followed in all groups that used µCT) also appeared to be quite fruitful.

As mentioned in the project title (Thermal Impact on the Damaged Zone), a significant effort has been made during the project on the characterisation of the effects of temperature on the permeability of discontinuities through various original experimental devices. The discontinuities investigated were of different natures. As shown by X-ray µCT, pre-existing discontinuities on so-called "intact" samples appeared to be quite significant, particularly in the case of Opalinus clay. This of course is a concern when attempting to determine constitutive parameters describing the shear behaviour, since the samples to test appear not to be continuous because of pre-existing damage due to the sensitivity of the clays to excavation, drying, storage, transport and wetting. Note however that the situation is better for the Callovo-Oxfordian claystone compared to the Opalinus one. Note that Boom clay (a significantly more plastic stiff clay in the meaning of Soil mechanics) 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.

However, the permeability tests carried out independently in various laboratories by using different approaches on either pre-existing, artificial or shear discontinuities all provided permeability values that were closed to the matrix 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/claystones presently considered as possible geological barriers in Europe. This is perhaps one of the major achievements of the TIMODAZ project.

The effect of temperature on the behaviour (better known on Boom clay for some time) appeared to be comparable on claystones. Briefly, temperature tends to somewhat weaken the mechanical resistance of the clays. Also, thermal pore pressures induced when heating in undrained (or poor drainage) conditions have an effect on both the matrix and the fissures. The larger thermal dilation of water compared to that of the solid phase enlarges the fissures and permeability measurements indeed showed an increase in permeability. Some thermal damage in the matrix itself is also probably and would certainly deserve further attention. However, the effect of temperature cycles on the global permeability (matrix + fissures) is not significant and the final global permeability is close to the initial one. Note however that an induced thermal failure has been observed, confirming that temperature reduces the resistance of a fissured material.

Finally, thanks to a significant thermo-hydro-mechanical experimental program carried out with specific and sophisticated devices on very low permeability clay/claystones specimens difficult to test, the TIMODAZ project experimentally demonstrated the excellent self-sealing behaviour of the specimens tested, both under isothermal ambient temperature and after temperature cycles. Also, the various behaviour features investigated during WP3.1 and the parameters derived have been of interest for the WP5 tasks devoted to numerical modelling.

6.3.4 Publications

International Journals with reviewing committee

- Lenoir N., Bornert M., Desrues J., Besuelle P., Viggiani G. (2007). Volumetric digital image correlation applied to X-ray micro tomography images from triaxial compression tests on

argillaceous rock. Strain, 43, 193-205.

- Chen GJ, Maes T, Vandervoort F, Sillen X, van Marcke P, Honty M and Vietor T. "Thermal impact on damaged Boom clay and Opalinus clay: Permeameter test and Isostatic test from the TIMODAZ project" to be submitted to *"Applied Clay Science"*.
- Monfared M., Delage P., Sulem J. , Mohajerani M., Tang A.M. and De Laure E. A new hollow cylinder triaxal cell to study the behaviour of low permeable materials. *International Journal of Rock Mechanics and Mining Sciences*, doi 10.1016/j.ijrmns.2011.02.017.
- Monfared M., Sulem J., Delage P., Mohajerani M. On the THM behaviour of a sheared Boom clay sample: application to the behaviour and sealing properties of the EDZ. Submitted to *Engineering Geology* (March 2011).
- Monfared M., Sulem J., Delage P., Mohajerani M. A laboratory investigation on the thermal properties of the Opalinus claystone. Submitted to *Rock Mechanics and Rock Engineering* (March 2011).

Book Chapter

- J. Sulem, M. Monfared, A.-M. Tang, P. Delage, 2010. "Thermo-mechanical behavior of clayey rocks for application to nuclear waste disposal storage". Capitulo 5 in *"Meccanica Ingenieria della Rocca"*, G. Barla Ed. Torino, December 2010.

International/national conference proceedings/presentations

- Monfared M., Delage P., Sulem J., Tang A.M. and De Laure E. 2010. Un nouvel appareil triaxial à cylindre creux pour l'étude des roches peu perméables. *Réunion Technique du Comité français de Mécanique des roches*, Paris, March 2010.
- Zhang, C.-L., Rothfuchs, T., Su, K. "Laboratory Experiments on Thermal Effects on Clay Rocks". Proceedings of the 3rd International Symposium GeoProc'2008 edited by J.-F. Shao and N. Burlion, "Thermo-Hydromechanical and Chemical Coupling in Geomaterials and Applications", 2008, 239 – 249.
- Delage P., Sultan N., Cui Y.J. 2009. Permeability changes of Boom clay with temperature. European Conference on "Impact of, THMC processes on the safety of underground repositories", Luxemburg, 29 September.
- M. Monfared, J. Sulem, M. Mohajerani, P. Delage, A.M. Tang, E. De Laure 2009. Détermination de la perméabilité de l'argile de Boom et conditions de réalisation des essais drainés. 19ème Congrès Français de Mécanique Marseille, 24-28 août.
- M. Monfared, J. Sulem, M. Mohajerani, P. Delage, A.M. Tang, E. De Laure, 2009. Permeability measurement of low permeability clay by means of a transient test. European Conference on "Impact of THMC processes on the safety of underground repositories", Luxemburg, 29 September.
- Zhang, C.-L, Wieczorek, K., Xie, M.-L. (2009): Swelling experiments on mudrocks, International Symposium on Unsaturated Soil Mechanics and Deep Geological Nuclear Waste Disposal (UNSAT-WASTE 2009), 24-28 August 2009, Shanghai, China.

6.4 WP 3.2 - Laboratory experiments: Mineralogic changes / Input for THMC analysis

6.4.1 Objectives of WP 3.2

This work package aims to determine the possible thermally induced modifications of clays mineralogy which is a dominant factor influencing the key properties of the clays and THM behaviour. The

investigation in this sub-workpakage provide thus key elements to answer the following questions:

- Under which thermal condition can the favourable clay properties are modified?
- Under which conditions do the changes in clay properties become irreversible?

Specific attention is given to the possibility of the creation of irreversible changes.
An ultimate temperature limit in terms of geochemical properties can be assessed through these analyses. The impact of these modifications of the geochemical properties on the hydro-mechanical behaviour of the clays can be qualitatively assessed.

6.4.2 Participants of WP 3.2

Only one participant: SCK.CEN

6.4.3 Key results/achievement/deliverables

To achieve the above objectives, lab experiments on the combined effect of temperature and oxidising or alkaline plume conditions on Boom Clay and Opalinus Clay were performed. The work performed within this workpackage comprised:

- the set-up of the batch experiments simulating the combined heat and chemical perturbations expected in the EDZ of the Boom Clay and Opalinus Clay
- the regular sampling of the leachates and subsequent chemical analysis (pH, Eh, TIC, TOC, Na, K, Mg, Ca, Si, Al, SO_4^{2-})
- the regular sampling of the solids and their mineralogical characterization (qualitative and quantitative XRD analysis, FTIR, SEM-EDX, CEC, TSA, UV-VIS)
- the measurements of the hydraulic conductivity in the intact and reacted Boom Clay and Opalinus Clay
- microscopic investigation (SEM-EDX) of the Boom Clay and Opalinus Clay permeameter cell test samples
- the acquisition and processing of the data, the interpretation and synthesis of the results in the context of the safety case

The results indicate no or very limited mineralogical changes in the both rock types for a set of heat and geochemical conditions within the experimental time frame. Low reactivity of clays is attributed to the presence of carbonates, which effectively buffer the pH disturbances in the system. Altogether, this study points to a good buffering capacity of both clays and highlights the role of the matrix to effectively prevent minerals from the reaction with the applied solutions.

In line with limited mineralogical alterations, no significant change occurred to safety-relevant clay properties, such as cation-exchange capacity or hydraulic conductivity as a result of chemical disturbance. The measurements of these parameters after the experiments closely approached the values reported for the non-disturbed clay host rocks.

It is evident that the heat phase in the history of the repository spans over longer time periods than the usual experiment lifetime. It is recommended that long-term experiments simulating coupled TC processes be performed in order to approach more realistic time frames. Important to note, the YCW (Young Cement Water) is more relevant to heat phase than ECW (Evolved Cement Water).

Detail report is given in D06/WP3.2- thermally induced modifications of clays

6.4.4 Publications

- Miro, etc. 2009 “Coupled Effects of Thermal and Geochemical Perturbations on the Mineral Stability of Boom Clay and Opalinus Clay: a Batch Experiment at 90°C” was accepted for

publication in the TIMODAZ-THERESA conference proceedings.

- Miro, etc. 2009 “Coupled Effects of Thermal and Geochemical Perturbations on the Mineral Stability of Boom Clay and Opalinus Clay: a Batch Experiment at 90°C” was accepted for publication in the TIMODAZ-THERESA conference proceedings.
- Honty, M., Wang, L., Osacky M., Uhlik P., Czimerova A., Madejova J. " Experimental interactions of the Opalinus Clay and Boom Clay with various repository relevant solutions at 90°C "submitted to the international journal *Applied Clay Science*

6.5 WP3.3 - Simulation tests /input for benchmark modeling

6.5.1 Objectives of WP 3.3

Within Workpackage 3.3 laboratory tests are performed simulating as close as possible the conditions in a real repository. This workpackage provides the experimental basis for validating the constitutive models that will be developed within the Timodaz project.

Precisely, the tests performed in WP3.3 aim to study in laboratory the fracturing and sealing processes that develop in the Excavation-Damaged Zone around galleries in clayey formations and the impact of a thermal phase on their evolution. For this purpose, simulation tests are performed on large/middle scale hollow cylinder samples with mechanical and thermal loadings similar to the evolution that will be encountered around disposal galleries for heat emitting radioactive waste. The results of these tests are used for modelling benchmark exercises in task 1 of WP 5.2. The hydraulic transfer properties through the tunnel face and through fractures are also characterised by drying tests.

6.5.2 Participants of WP 3.3

3 participants: EPFL, GRS and ULg

6.5.3 Key results/achievement/deliverables

Within this workpackage, three types of tests were performed:

- Middle scale hollow cylinder simulation tests on Boom clay and Opalinus clay by EPFL
- Combined damage and sealing tests, Large scale hollow cylinder simulation tests on COX by GRS
- Convective drying experiments by ULg

The deliverable of this workpackage can be found in D07/WP3.3- Laboratory simulation tests.

Middle scale hollow cylinder simulation tests on Boom clay and Opalinus clay by EPFL

Middle-scale hollow cylinder triaxial cell is developed in EPFL to perform the simulation tests with mechanical and thermal loadings fairly similar to the evolution that will be encountered around disposal galleries for heat emitting radioactive waste in laboratory in order to study the fracturing and sealing processes that develop in the Excavation Damaged Zone around galleries in clayey formations and the impact of a thermal phase on their evolution (**Figure 12**). In order to allow the X-Ray tomography of the sample inside the cell at different steps of the experiment, the usual steel body cell was replaced by the aluminium body cell. 4 GDS pressure controllers were equipped to the device to achieve an independent control of external confining pressure, internal confining pressure, external pore pressure, internal pore pressure. The developed device is thus able to

- Create an excavation damaged zone around the central hole of the cylinder
- Apply a thermal load in the central hole
- Carry out permeability (radial) measurements at different steps of the experiment
- Carry out tomography measurements at different steps of the experiment

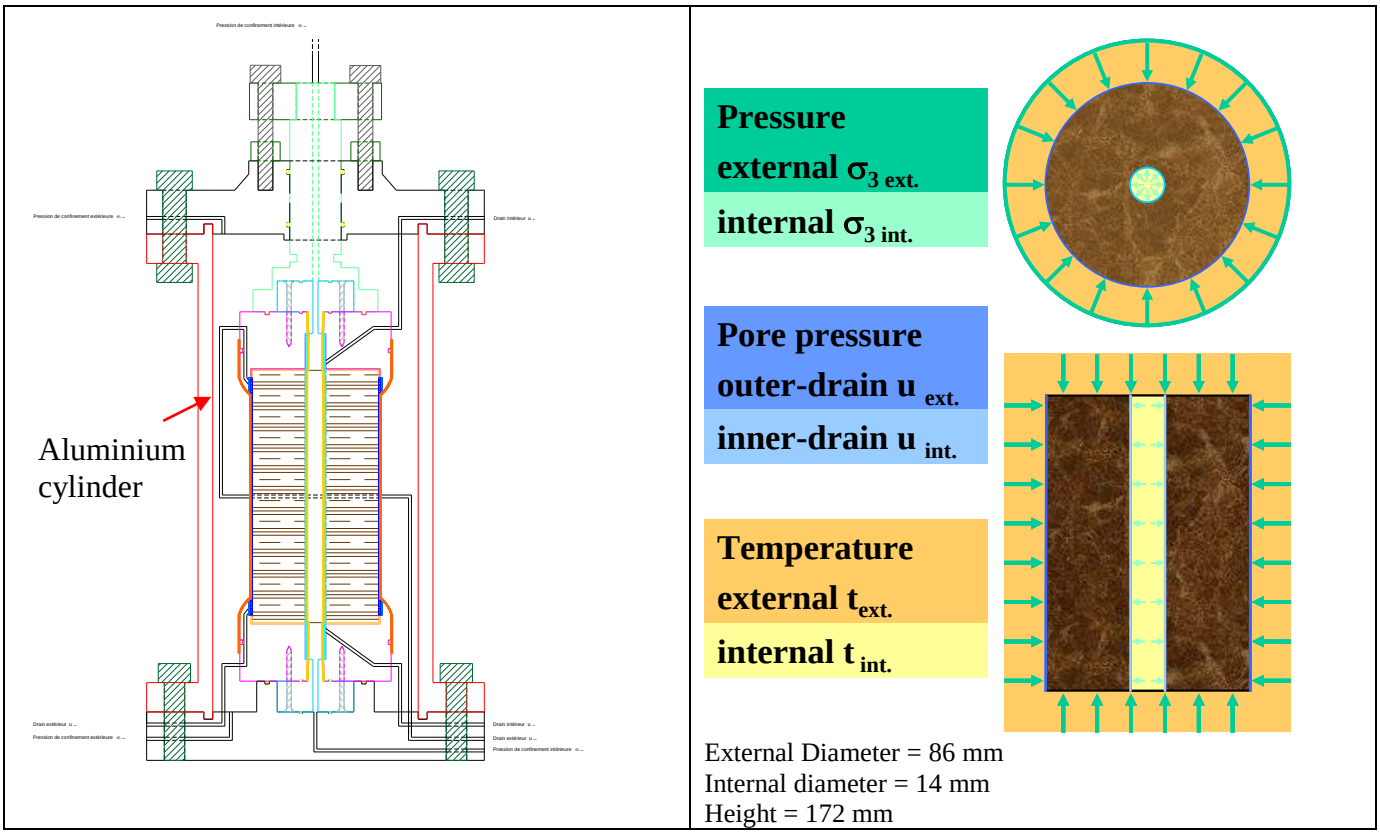


Figure 12: EPFL's Testing device for the simulation tests on hollow cylinder samples

The testing procedure is illustrated in **Figure 13**. Permeability measurements and X-Ray Computerized Tomography (XRCT) are carried out at different steps of the experiments. These results are then checked after disassembly of the test by visual inspection of saw-cut sections.

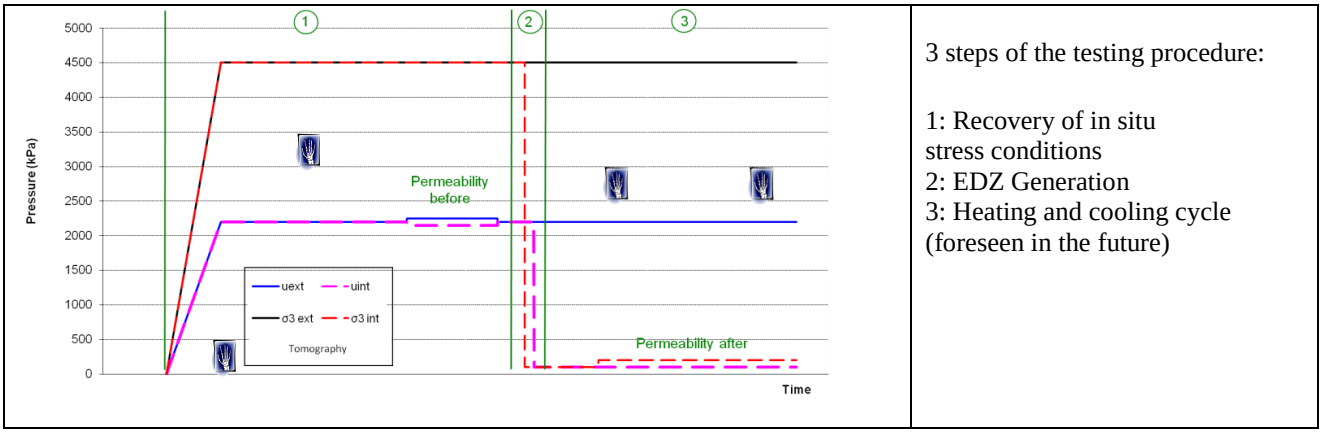


Figure 13: Stages of the testing procedure adopted for simulation tests in EPFL

Moreover, for tests on Boom clay, two different image processing methods are considered to investigate

the displacement around excavation:

- Digital Image Correlation (DIC) analyses, which allow to map the displacement field;
- Particle Manual Tracking (PMT), which consists in tracking the movement of pyrite inclusions identified in the images before and after the mechanical unloading.

The technical challenge faced to this simulation test is significant. Numerous trial tests were performed. Interesting results were obtained for both Boom clay and Opalinus clay. Detailed results and analysis of results were reported in D07/WP3.3 - Laboratory simulation tests..

Figure 14 shows results obtained from the tracking of pyrite inclusions after mechanical unloading (simulating excavation) on a Boom clay sample cored parallel to bedding plane. It points out the significant influence of the bedding planes on the mechanical behaviour of Boom Clay. This anisotropic displacement field was obtained and confirmed by DIC imaging process. One observes that the convergence near the hole is higher in the direction parallel to the bedding planes than in the perpendicular one, and a reverse trend is observed further inside the sample, which can be considered as "elastic" zone. This observation is consistent with the in situ observation in Boom Clay. During the excavation of the connecting gallery and Praclay gallery in Mol, it was observed that the convergence appeared to be higher in the horizontal direction (so parallel to bedding) than in the vertical direction (so perpendicular to bedding) (for Praclay gallery, 81 mm versus to 55 mm, a ratio of about 1.5). The difference in convergences in the “elastic” zone in the directions parallel and perpendicular to bedding seems roughly in agreement with the anisotropic elastic moduli back-analysed from the ATLAS experiment at Mol (see WP4.2).

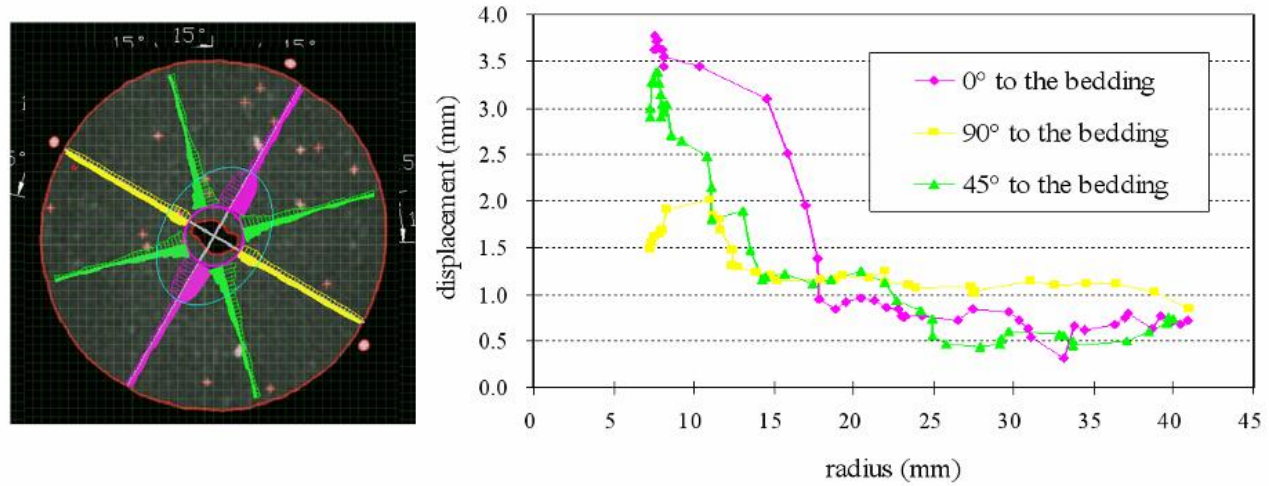


Figure 14 : Example of results obtained from the tracking of pyrite inclusions in the X-Ray scans (Boom clay) Radial convergence determined along three directions: parallel to bedding (magenta curve), perpendicular to bedding (yellow curve) and at 45° (green curve). Original diameter of inner hole: 14 mm

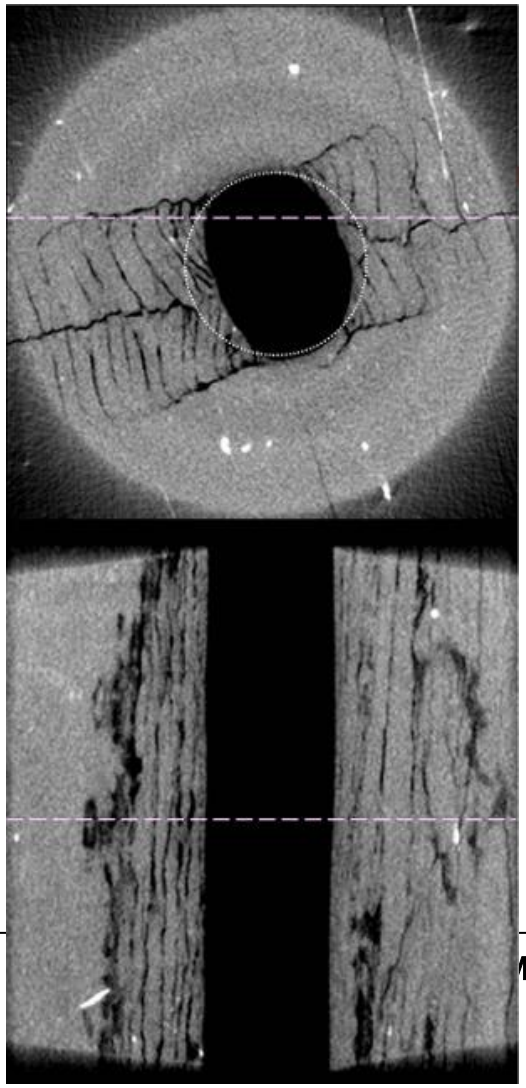
Figure 15 gives an example of test results on one Opalinus clay sample cored parallel to the bedding. After the removal of the sample from the testing cell, high resolution X-Ray Computerized Tomography (XRCT) of the central part of the sample was performed. The technique revealed the fracture pattern that developed around the central hole. The cross sections show cracks mainly along the bedding planes (indicated by the white lines). The bedding plane failure is followed by buckling, rotation and slab-like breakouts in two regions that extend from the borehole normal to the bedding. The slab thickness is regular but increases systematically away from the borehole. The width of the deformed region is similar to the diameter of the borehole. In axial direction the fractures constitute a connected network (**Figure 15**, lower left). After impregnation of the sample with resin and saw cutting normal to the hole

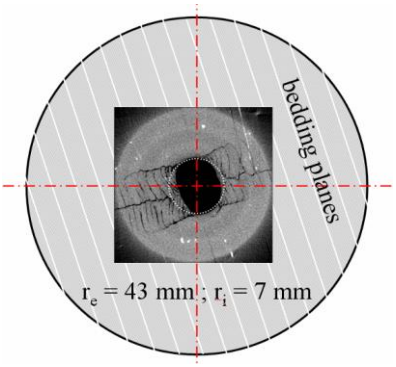
axis, the bedding controlled “Excavation” Damaged Zone was clearly visible (lower right picture of **Figure 15**).

Permeability measurements under radial convergent flows and X-Ray tomography scans were carried out before and after the decrease of the central hole pressure from 4.5 MPa to 0.2 MPa. A small increase in permeability (about 40%) and a slight decrease in rock density around the borehole (detected in the tomography) suggest that a damaged zone has been induced around the central hole by the mechanical unloading.

It is worthwhile to note that, at the Mont Terri URL, distinct fracture patterns are observeddepending on the orientation of boreholes/galleries with respect to the bedding planes (Blumling et al. 2006). **Figure 15** revealed the development of a fracture pattern around central hole after mechanical unloading on a sample cored parallel to the bedding. The geometry and extent of the "Excavation Damage Zone" induced in this laboratory simulation test are quite similar to breakout patterns around openings parallel to bedding in the Mont terri URL. A striking similarity is also found with the fracture pattern observed in the borehole EDZ pattern observed in Mont Terri in the frame of Timodaz in situ test (WP4.1) as shown in **Figure 16.**

The analogical displacement field obtained by the simulation tests performed on Boom clay with the in-situ observation in Mol, the similar fracture pattern obtained by XRCT on Opalinus clay with the in situ observation in Mont Terri URL constitute without doubt an important outcome of TIMODAZ project, since they increase the understanding of mechanism of the EDZ process around excavation and increase significantly the confidence for the upscaling and transfer of knowledge from the lab test results to in situ results and final towards the full scale repository concepts.





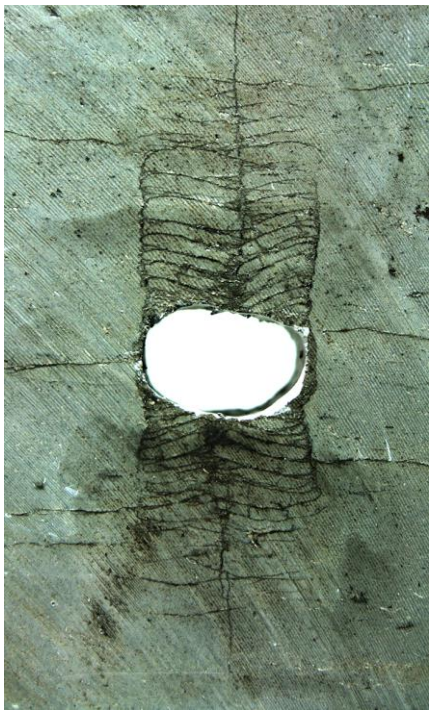


Figure 15 : Fractures pattern observed after the laboratory test (i) by means of a high resolution XRCT (left and upper right pictures; Phoenix scans) and (ii) visually after sawing of the *of the sample (lower right). Original diameter of the inner borehole: 14 mm.*

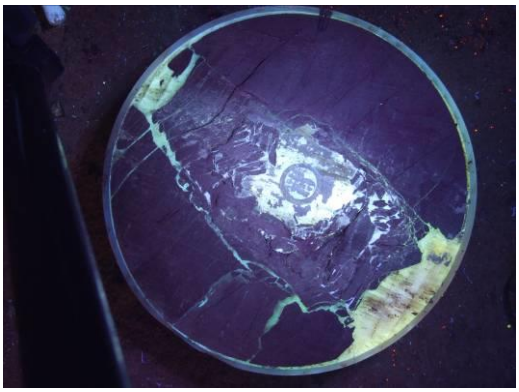


Figure 16 : borehole EDZ observed in Mont Terri : Section of the overcore from 8.32 m under UV light. Bedding planes from lower left to upper right. Resin (light blue/green) delineates fracture network around the central borehole.

Combined damaging and sealing tests on COX by GRS

Objectives : The damage and sealing of clay rocks has been intensively investigated in the frame of the recent EC projects such as MODEX-REP (Zhang & Rothfuchs, 2004; Su 2007), SELFRAC (SELFRAC 2004) and NFPRO (Davy et al. 2007; Popp & Salzer, 2007; Zhang et al., 2006/2007). However, very limited data are available, particularly for the permeability behaviour related to damage and re-compaction. In order to enhance the knowledge about this issue, a series of combined damage and re-compaction experiments were performed by gas flowing through samples under various confining stresses (Figure 17)

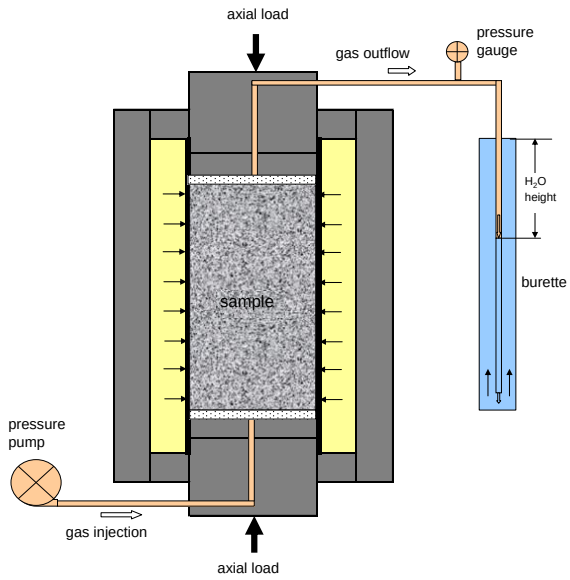


Figure 17 : Principle of triaxial compression tests with permeability measurement

Samples of the Callovo-Oxfordian argillite (COX) were taken from borehole REP2206 which was drilled vertically from the floor of the -445-m niche to a depth of 467 m at the Bure-URL.

A test procedure consisting of damage and re-compaction phases was applied to each sample at ambient temperature of 25±1°C. **Figure 18** shows a typical test with the evolution of applied axial/radial stresses, measured axial strain and gas permeability. Each sample was first loaded to an isotropic stress in a range of 2 to 10 MPa, and then by keeping the radial stress, the axial stress was increased either at stress rates of $1 \cdot 10^{-5}$ to $1 \cdot 10^{-4}$ MPa/s or comparable strain rates of $2 \cdot 10^{-8}$ to $8 \cdot 10^{-8}$ s^{-1} to failure. The failure occurred so quickly that the confining stresses were simultaneously regulated by the testing system itself to stabilize the sample. After that, the damaged samples were re-compacted by application of different loading paths.
By this way, the evolution of the gas permeability during damage phase and re-compaction phase was characterised. The following conclusions can be drawn:

1. Dilatancy induced by deviatoric loading appears after elastic yielding due to micro-fracturing. The growth and coalescence of fractures is a percolation process. As the percolation threshold is exceeded, the permeability increases drastically by several orders of magnitude, depending on the confining stress. Based on the current data base, a very preliminary damage concept is proposed for identification of dilatancy, percolation, and failure boundaries in the stress space.

2. Re-compaction and permeability reduction of fractures is dominated by the normal stress. The permeability reduction related to the normal stress on fractures can be empirically approached by an exponential function.

3. More precise experiments and theoretical studies are needed to improve the data base and to develop constitutive models for the damage and sealing behaviour of fractures in argillites.

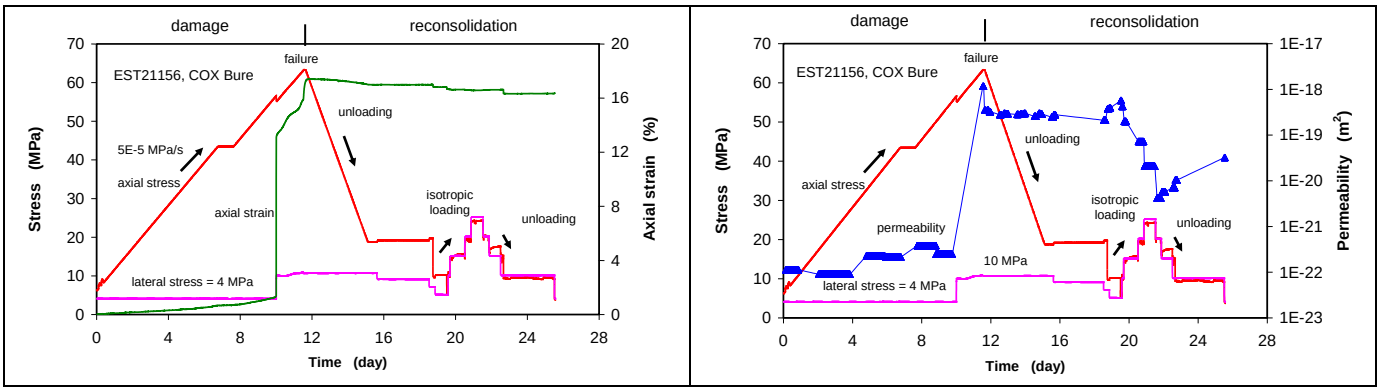


Figure 18: Measurements of stress-strain-permeability on COX sample EST21156

Large scale hollow cylinder simulation tests on COX by GRS

Figure 19 shows the layout of the large hollow cylinder triaxial simulation test cell developed in GRS. Permeability changes of the hollow cylinder are monitored in axial direction by injecting nitrogen gas or synthetic formation water to the bottom at constant pressure and by measuring outflow at the top.

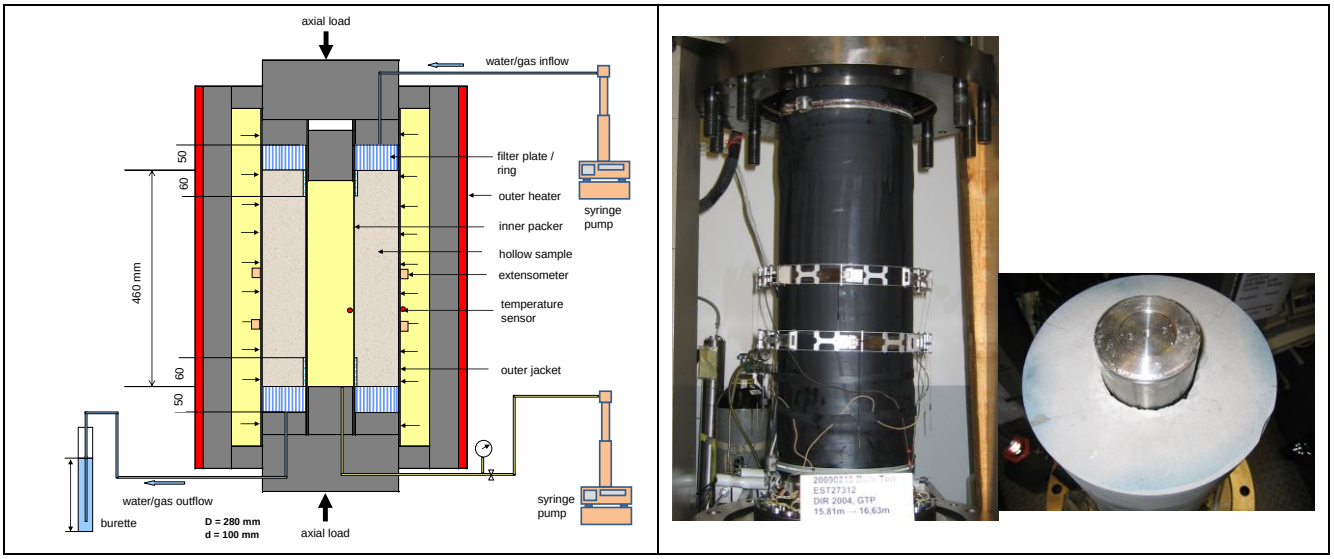
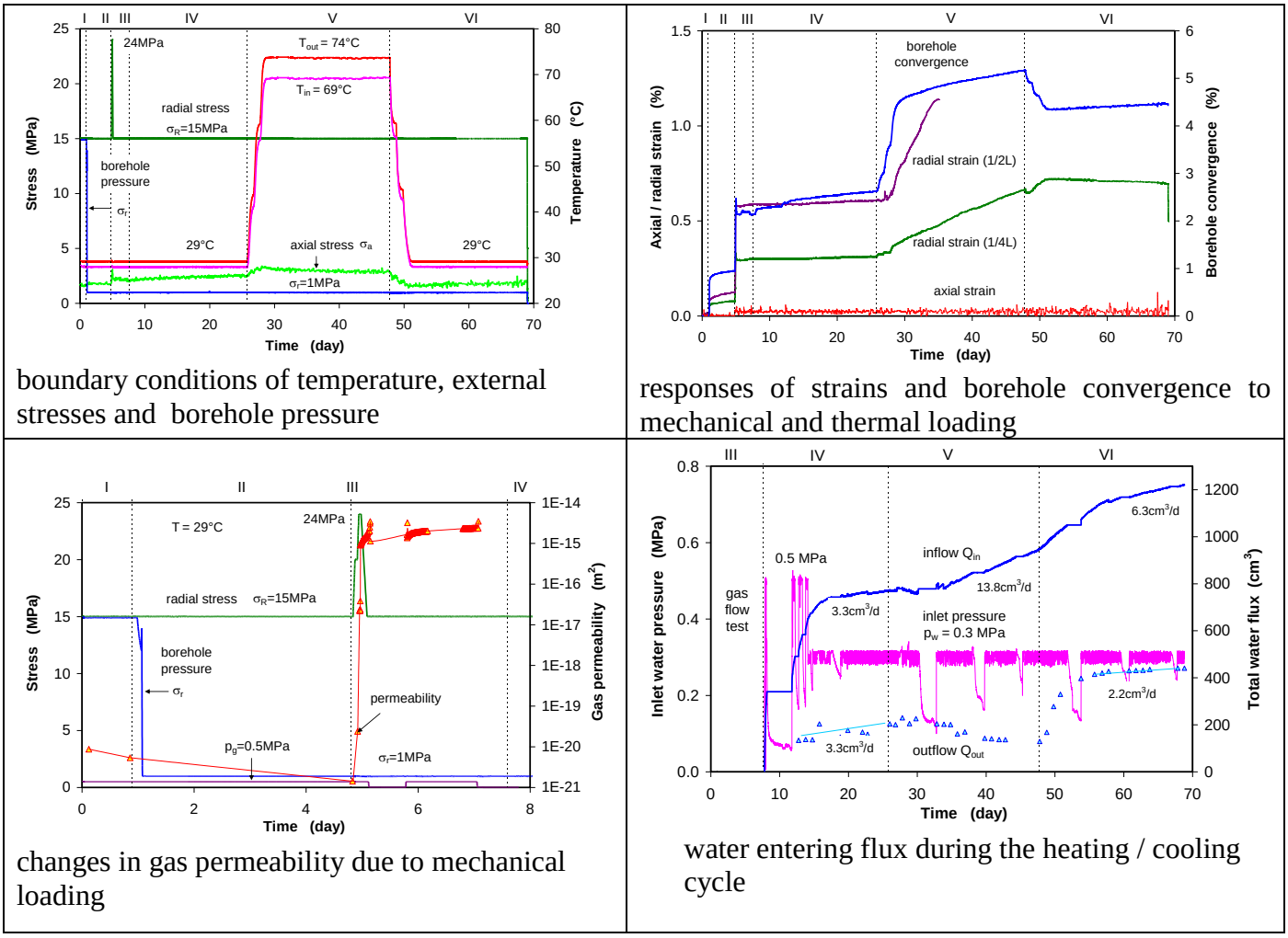


Figure 19 : Test layout for simulation of damaging and sealing of claystone around a borehole in a large cylindrical sample in the GRS triaxial apparatus

The simulation test results given in Figure 20 comprises following steps:

I. Determination of initial state of the hollow cylinder and Pre-consolidation of the sample at increased compressive load to approach the original rock state
II. Borehole excavation: From the re-consolidated state, the borehole excavation was simulated by reducing the borehole pressure down to σ_r = 1.0 MPa.
III. EDZ-intensification: In order to determine the critical condition for generating a flow pathway around the borehole, the external stress was further increased.
IV. Water injection: In order to simulate formation water flow towards the EDZ, synthetic pore water was introduced to the top of the fractured sample.
V. Heating was performed by increasing the boundary temperature step by step.
VI. Cooling phase followed by reducing the temperature stepwise
VII. Dismantling and post-testing



boundary conditions of temperature, external stresses and borehole pressure

responses of strains and borehole convergence to mechanical and thermal loading

changes in gas permeability due to mechanical loading

water entering flux during the heating / cooling cycle

Figure 20 : Results of BMT test 4 on a large hollow sample DIR1004-EST27312

Detail analysis of the test results were given in the corresponding deliverable 7 (D07/WP3.3- Laboratory simulation tests).

The simulation tests performed by GRS on COX provided a set of data base for the validation of the constitutive models and computer codes used for analysing THM processes in the excavation damaged zone in argillaceous rock surrounding a nuclear waste repository.

Convective drying experiments by ULg

In the context of radioactive waste disposal the required ventilation of the underground drifts during the construction and operational phases of repository could give rise to a desaturation process of the rock around the cavities. The characterization of the hydraulic transfers occurring at the ventilated cavities wall is an important issue in geomechanics, because they modify the capillary pressure distributions in argillaceous rocks in contact with the atmosphere. The capillary pressure distributions are indeed needed in order to predict the development of an excavated damage zone around the cavities. It emphasizes the need of correct flow boundary conditions in order to reproduce the hydraulic exchanges at the galleries wall.

This problem can be related to the drying of an unsaturated porous medium, which is a process of

moisture removal from materials. The study of the drying mechanisms can be performed through drying tests on soil samples. Such experiments are indeed interesting, because they reproduce the conditions of the required ventilation in the underground tunnels.

In order to improve the understanding of the moisture transfers into the porous medium and the exchanges with the atmosphere different convective drying experiments have been performed on soil samples within Timodaz project. In a preliminary study Awans silt samples have been dried in order to understand the drying processes. Then new drying tests are performed on Boom clay with different air relative humidities and air velocities. However, the tests results are auspicious, other experimental drying tests should be performed on Boom clay with new drying conditions closer to the natural ventilation conditions.

The experiments are analyzed assuming the presence of a boundary layer at the surface of the porous medium. Heat and vapour transfers take place therein, in addition to the heat and water flows which occur into the porous medium. Mass and energy exchanges in the boundary layer are controlled by mass and heat transfer coefficients characterizing the boundary layer. The exchange coefficients can be determined through the experimental results for the different drying conditions. The formulation of a new thermo-hydraulic boundary finite element is developed. This thermo-hydraulic boundary condition based on the existence of a boundary layer allows a good numerical reproduction of the kinetic of the materials desaturation quantified during the drying experiments.

The developed hydraulic exchanges model could be extended and improved in the context of radioactive waste repository. Indeed, in weakly permeable geological layers, gas overpressures can be generated, which modify the kinetic and the mechanisms of the desaturation of the rock mass. Gas overpressures can no more be disregarded and has to be taken into account.

6.5.4 Publications

International journals

- Zhang, C.-L., Rothfuchs, T.: *Damage and sealing of clay rocks detected by measurements of gas permeability*. in the journal “Physics and Chemistry of the Earth” 33 (2008) S363-S373
- Pierre Gerard, Robert Charlier, René Chambon, Frédéric Collin (2008) - *Influence of evaporation and seepage on the convergence of a ventilated cavity* - Water Resources Research (doi:10.1029/2007WR006500), in press.
- Gerard P., Léonard A., Masekanya J.P., Charlier R., Collin F. "Study of the soil-atmosphere moisture exchanges through convective drying tests in anisothermal conditions", *International Journal for Numerical and Analytical Methods in Geomechanics*, **34**, pp.1297-1320, 2010.
- Zhang, C.L, Wieczorek, K., Xie, M.L.: "Swelling experiments on mudstones", *Journal of Rock Mechanics & Geotechnical Engineering*, 2010, 2(1): 41-47.
- Zhang C.L.: "Experimental Evidence for Self-sealing of Fractures in Claystone", *Physics and Chemistry of the Earth (accepted).*

International /national conference

- Zhang, C.-L., T. Rothfuchs, K. Wieczorek, H.-J. Herbert: *Experimental Study on Self-Sealing of Indurated Clay* , on the symposium "Fault Zones: Structure, Geomechanics and Fluid Flow", Geological Society London, 16-18, September 2008
- Pierre Gerard, Robert Charlier, Frédéric Collin (2008) - *On boundary condition in tunnels under partial saturation* - Proc. First European Conference on Unsaturated soils, 2-4 July 2008 (Durham), 6p.
- Zhang C.-L.: *Self-sealing of Fractures in Argillites under Repository conditions*, on the

international conference and workshop in the framework of the EC TIMODAZ and THERESA projects, 29th Sept. – 1st Oct. 2009, Luxembourg.

- Gerard P., Bernardino J., Léonard A., Charlier R., Collin F. – *Convective drying tests of silts: Experimental study* – Proc International Symposium SEC2008, 6 p., Paris (F), 1-3 September 2008.
- S. Levasseur, P. Bésuelle, F. Collin, R. Chambon, R. Charlier, G. Viggiani – *EDZ in clayey rocks: which effect on permeability?* – Proc EC-TIMODAZ-THERESA THMC conference, 10 p., Luxembourg (L), 29 Sep. – 01 Oct. 2009.
- P. Gerard, A. Léonard, R. Charlier, F. Collin – *Characterization of vapour transfers in non isothermal conditions at cavities wall using convective drying tests* – Proc EC-TIMODAZ-THERESA THMC conference, 5 p., Luxembourg (L), 29 Sep. – 01 Oct. 2009.
- V. Labiouse, T. Vietor, "Laboratory and in Situ Simulation Tests of the Fracturing in the EDZ around Galleries in Opalinus Clay", to be published in the proceedings of the international conference and workshop in the framework of the EC TIMODAZ and THERESA projects, 2009, Luxembourg. 5 pp.
- V. Labiouse, S. Escoffier, L. Gastaldo, J.-F. Mathier "Self-Sealing of Localised Cracks in Boom and Opalinus Clay Hollow Cylinders". to be published in the proceedings of the international conference and workshop in the framework of the EC TIMODAZ and THERESA projects, 2009, Luxembourg, 5 pp.
- S. You, V. Labiouse, L. Vigne, L. Gastaldo, M. Bernasconi "Medium resolution X-Ray Computed Tomography of hollow cylindrical samples of Boom Clay". Proceedings of the European Rock Mechanics Symposium EUROCK 2010, Lausanne, Switzerland, 15 - 18 June 2010, pp. 755-758.
- V. Labiouse "Damaged Zone around radioactive waste disposal in clay host rocks". Invited lecture at the European Rock Mechanics Symposium EUROCK 2010, Lausanne, Switzerland, 15 - 18 June 2010.
- P. Gerard, A. Léonard, R. Charlier, F. Collin – On the modelling of convective drying tests on soil samples in non-isothermal conditions – Proc. 17th International drying Symposium(IDS 2010), 8 p., Magdeburg, Germany, 3-6 october, 2010.
- Zhang, C.L., Wieczorek, K., Rothfuchs, T., Armand, G., Lebon, P.: "Responses of the Opalinus Clay to Heating during the HE-D Experiment at Mont Terri", to be published in the proceedings of the international conference and workshop in the framework of the EC TIMODAZ and THERESA projects, 2009, Luxembourg.
- Zhang C.L.: "Self-sealing of Fractures in Argillites under Repository conditions" to be published in the proceedings of the international conference and workshop in the framework of the EC TIMODAZ and THERESA projects, Sept. 2009, Luxembourg.

6.6 WP4.1 – small scale In-situ experiments

6.6.1 Objectives of WP 4.1

The objective of this workpackage is to realise small scale in-situ tests to characterise the influence of the thermal load on the THM behaviour and the sealing capacity of clays. One experiment is realised at Mont Terri in Opalinus Clay and another one at Mol in Boom Clay. The results of these experiments are used for benchmark exercises.

6.6.2 Participants of WP 4.1

3 Participants : NAGRA, Solexperts and EURIDICE

6.6.3 Key results/achievement/deliverables

Two in-situ tests were performed in this workpackage:

- The SE excavation and the SE-H heated borehole test at Mont Terri URL (NAGRA)
- Small scale in situ heater test ATLAS III in HADES URL, Mol (EURIDICE)

The SE excavation and the SE-H heated borehole test at Mont Terri URL

The experiment in the Mont Terri rock laboratory focussed on the damage formation around excavations and the self-sealing under isothermal and non-isothermal conditions. Although the SELFRAC experiments 1 and 2 at Mont Terri clearly demonstrated the self-sealing capacity of the Opalinus Clay, the understanding of the underlying processes was still incomplete. The work performed in the TIMODAZ in-situ experiment at Mont Terri rock laboratory was intended to provide the information and data for a basic understanding of the observed phenomena and add information on the influence of temperature increase on the self-sealing process.

The experiment at Mont Terri URL consisted of 2 phases :

- Phase A: the excavation of a previously tested borehole (EU Project SELFRAC) improved the understanding of EDZ geometry and formation in bedding parallel boreholes as a small-scale equivalent to repository tunnels.
- Phase B: a heated experiment (SE-H) has been conducted to investigate the strongly coupled mechanical and hydraulic effects of heating on the self-sealing of the EDZ.

Activities and results of the Phase A

After completion of the overcoring, the retrieval of the cores and the cutting the sections of the overcore from the SELFRAC test were analysed and a conceptual model of the borehole EDZ was elaborated as planned (**Figure 21** and **Figure 22**).
The fracture pattern is similar to that obtained in the simulation test performed by EPFL as mentioned in § 6.5.

Figure 21 : Drilling crew with overcoring equipment for the old SELFRAC borehole in the Mont Terri URL. Outer diameter of the double core barrel is 380 mm.

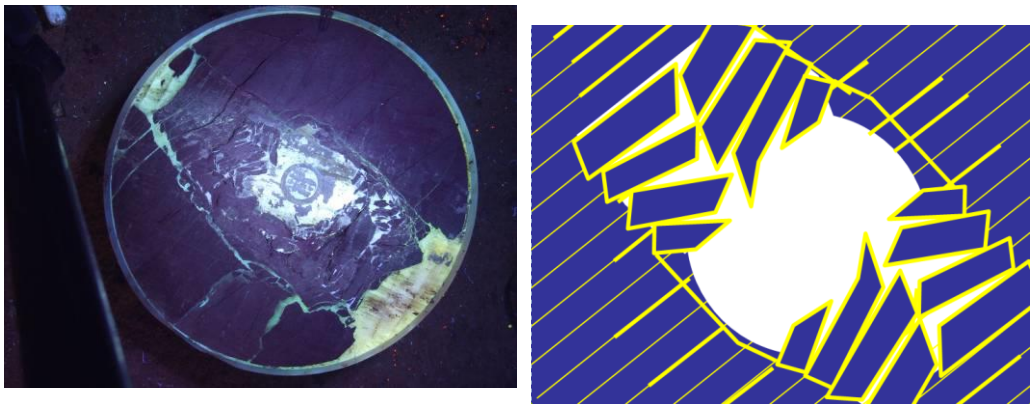


Figure 22: Section of the overcore from 8.32 m under UV light. Bedding planes from lower left to upper right. Resin (light blue/green) delineates fracture network around the central borehole. Note the perfect positioning of the old (diameter 101 mm) borehole in the overcore (diam. 330 mm). Right: conceptual sketch of the breakdown of the unsupported borehole.

Activities and results of the Phase B

In the second phase of the small scale in-situ test at Mont Terri a non-isothermal borehole test was undertaken. The test allowed to investigate the hydraulic conductivity of the EDZ around the packer seals also at elevated temperatures (up to 90°C). Hydraulic tests were conducted before, during and after stepwise heating of the host rock.

A first borehole was equipped with a large size double packer system (300 mm) in September 2007. This test site had to be abandoned because of a system leakage of unknown origin. A new test system with a smaller diameter (76 mm) was then constructed and installed in Summer 2008 in a borehole in the shaly facies of the Opalinus Clay at the Mont Terri rock laboratory. At some distance from the heater the far field was also equipped with sensors for pore pressure and temperature measurements (**Figure 23**)

A first hydrotest campaign was performed and evaluated in mid 2008 showing low transmissivities. Testing of the system and the characterisation of the surrounding rock mass and EDZ was completed in early 2009.
Circulation of heated water through the lower packer of the system was switched on in April 2009. Subsequently the temperature was then increased in several steps during in 2009 to 65°C. During these steps the packer pressures in the heater were held constant while the interval pressures were allowed to increase.
During the stepwise temperature increase the pressure and temperature evolution in the heating system and the surrounding rock was continuously monitored by the sensor array in the heater. Pressures and temperatures were also monitored in the two boreholes BSE-H3 and –H4 at 70 cm from the heater in the Opalinus Clay.
As expected each temperature increase in the lower packer element led to a corresponding increase in pressure in the adjacent test intervals of the heating system.

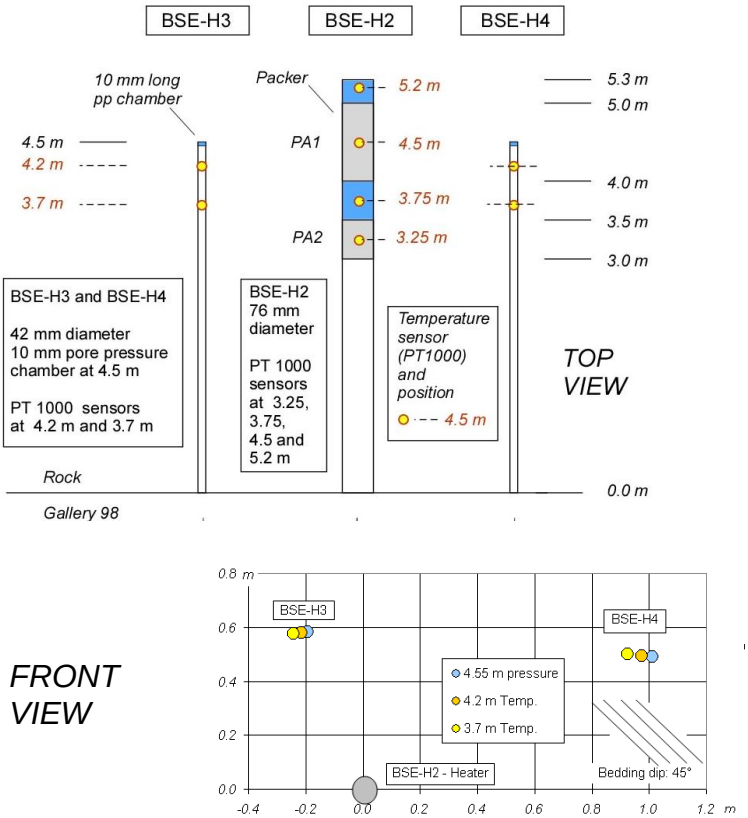


Figure 23 : Borehole configuration in top view (top) and in front view (bottom). Pa 1 and Pa 2 are the packers seperating the two test intervals 1 and 2, designated Int 1 and Int 2, whereby Int 1 is located below Pa 1 between 5 and 5.3 m depth.

The pressure and temperature increase in the rock could be picked up in the observation boreholes. The propagation of the pressure and temperature signals in the rock normal and parallel to bedding differs significantly (Figure **24**). The temperature induced pore pressure increase in the observation intervals of the heater has constantly increased with increasing test temperature. These changes apparently have been irreversible as the pore pressure drops during cooling maintain these high gradients. Possibly thermal compaction or plastification in the vicinity of the heater borehole leads to a stiffening of the matrix. Alternatively the transmissivity in the heater nearfield may have been reduced by self-sealing effects.

Two constant head tests were conducted to monitor the evolution of the nearfield hydraulic properties during the heated stage. Between test HI1 and HI2, the drawdown curve changed at middle time indicating an increase in transmissivity by a factor of about 1.8 suggesting the creation of damage along the bedding planes.

After temperature step T_02 and a corresponding temperature increase in interval 2 to 32.8° C, the transmissivity decreased by a factor of about 1.6 and remained stable for the next hydraulic test HW1 when the interval temperature reached about 65.3°C. The calculation of the intrinsic permeability however shows a continuous decrease of this fluid and temperature independent parameter by a factor of about 4 from test HI2 to test HW1 (Figure 25).

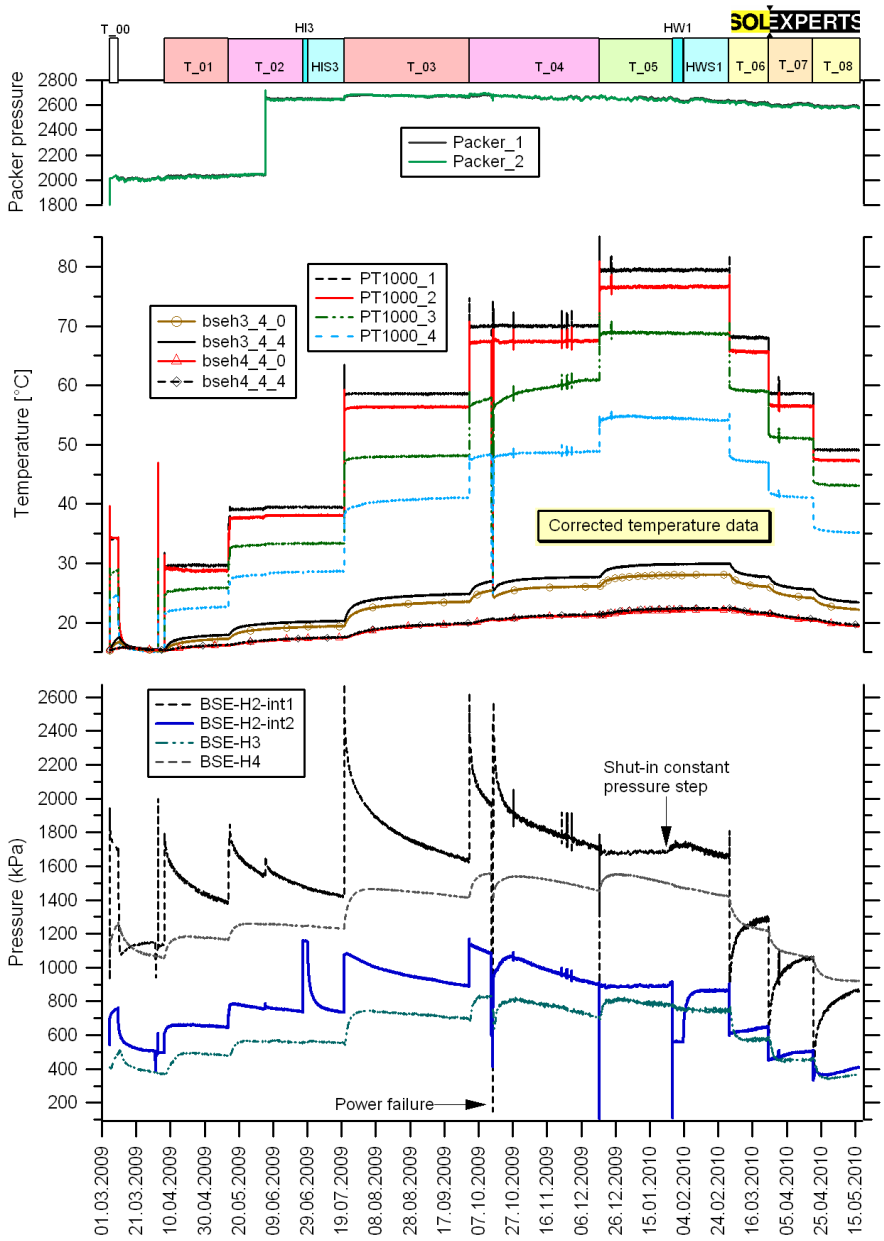


Figure 24: SE-H Small scale in situ test at Mont Terri. Temperature and pressure evolution (BSE-H2: heater borehole, BSE-H3/-H4: pore pressure observations recorded at 60 cm and 120 cm from the heater in the directions normal and parallel to the bedding, respectively

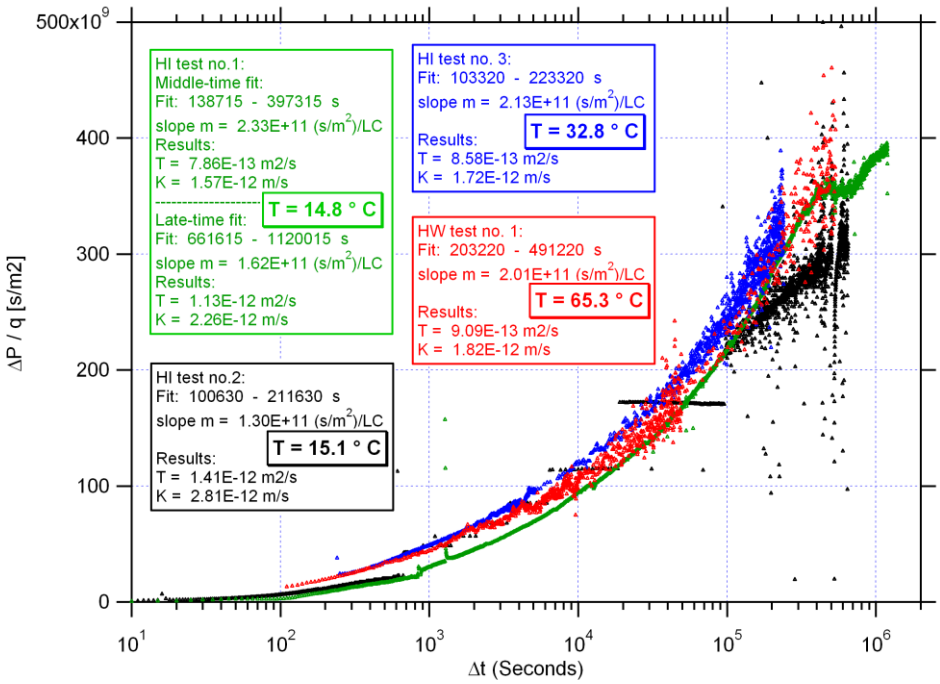


Figure 25: Comparison of drawdown curves of the different constant head tests performed in BSE-H2 interval 2.

Small scale in situ heater test ATLAS III at HADES URL, MOL

Contribution of EURIDICE to WP4.1 consists in realising the in situ small heater test in Mol URL HADES: ATLAS test (**A**dmissible **T**hermal **L**oading for **A**rgillaceous **S**torage) in order to have a better assessment of the THM characteristics of Boom Clay and to provide in situ THM responses for WP 5.2 to validate the developed numerical tools through the benchmark exercise.

The layout of the test is given in **Figure 26**. The heater is installed in the central borehole AT89E, both piezometers filters and thermocouples are installed in observation boreholes AT85E and AT93E, AT98E, while in AT97E, only thermocouples were installed.

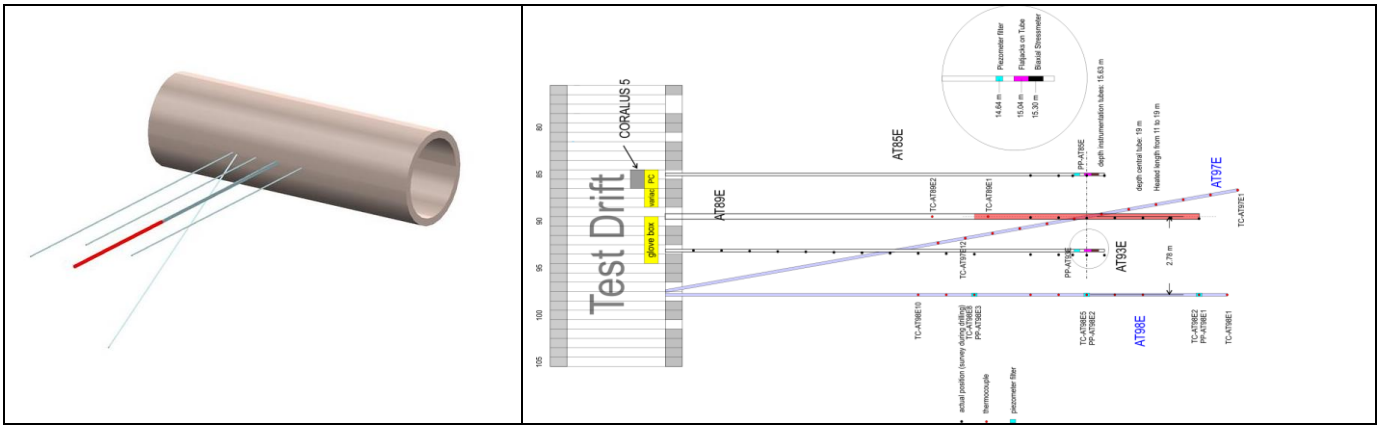


Figure 26 : lay out of small scale in situ heater test ATLAS III test

The heating phase has been switch on at 2nd of April 2007 step by step by heating power control and switch off on 2008-04-17. The in situ measurements obtained during ATLAS experiment were back-analyzed though numerical simulation.

The ATLAS III heating test has put in evidence of the following THM coupled behaviour of Boom clay:

- Thermal anisotropy: as shown in **Figure 27** , the temperature variations measured at two points having nearly same distance from heater but in different directions are quite different.
- Mechanical anisotropy: as shown in **Figure 28**, in all the five piezometers, the pore water pressure decrease temporaryly after increasing power and increase temporaryly after cooling, numerical investigation indicated that this temporary variation of pore pressure is related to the anisotropic mechanical behaviour.

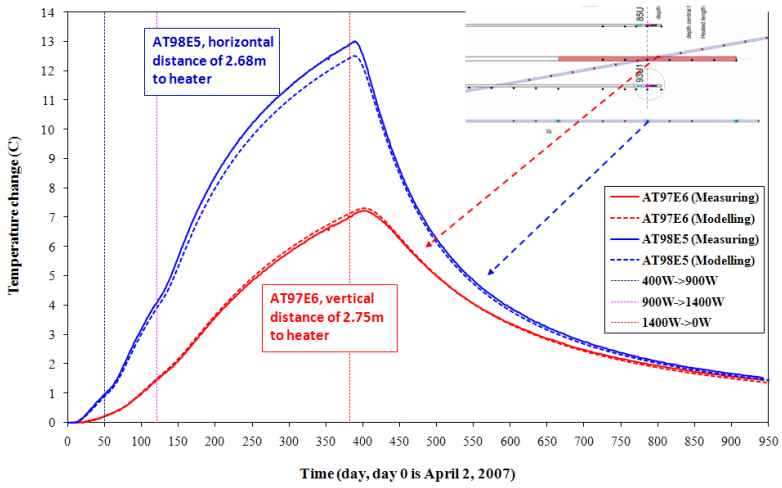


Figure 27: temperature increase in sensors TC-AT98E5 and TC-AT97E6.

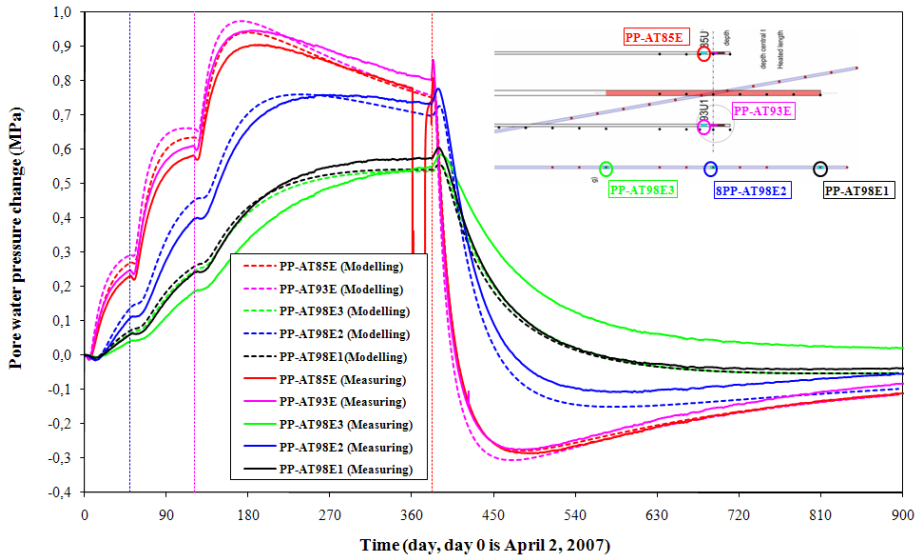


Figure 28: Comparison between measured pore water pressure and modelled one by employing three dimensional modelling and anisotropic THM parameters

General conclusions from small scale in situ tests:

The in situ permeability measurement at different temperature indicated that the temperature effect on the permeability concerns mainly on the fluid viscosity.

The successful realization of small scale in situ tests in HADES and MONT TERRI Underground

Laboratories have improved significantly the understanding of the coupled Thermal-Hydro-Mechanical processes during excavation and thermal loading phases in both Opalinus and Boom clays.

The test results and measurements obtained by small scale in situ tests provide valuable in situ data for validating the constitutive models developed within the TIMODAZ project.

The THM characteristics determined from small scale in situ tests for both clays are of important significance for the final repository designs in both clays: gallery spacing, etc.

Detailed analysis and interpretation of test results are given in the corresponding deliverable 8 (D08 /WP4.1- Small scale in situ tests).

6.6.4 Publications

International journal

- Chen GJ, Sillen X, Verstricht J, and Li XL " ATLAS III In Situ Heating Test in Boom Clay: Field data, observation and interpretation" accepted for publication in the international journal *Computers and Geotechnics,*

International/national conference

- V. Labiouse, T. Vietor, *Laboratory and in Situ Simulation Tests of the Fracturing in the EDZ around Galleries in Opalinus Clay*, To be published in the proceeding of the EC-TIMODAZ-THERESA THMC conference, 5 pp.
- Garitte B., Sillen X., Li X.L, Armand G., Vaunat J. and Gens A. 2009. "Comparative study of three in-situ heating tests in anisotropic media: the HE-D, TER and ATLAS experiments" To be published in the proceeding of the EC-TIMODAZ-THERESA THMC conference.

6.7 WP 4.2 - THM large-scale in-situ test PRACLAY

6.7.1 Objectives of WP 4.2

A large-scale heater test (PRACLAY experiment) is realised in the frame of the Belgium programme. The objective of this workpackage is to inform the partners about the progress of this test and to gather all necessary data for a "blind prediction" benchmark exercise. A part of the workpackage is also devoted to the interpretation of the seismic measurements performed around the PRACLAY experiment.

6.7.2 Participants of WP 4.2

2 Participants :

- EURIDICE: installation/conduction of Praclay experiment
- ASC: interpretation of the seismic measurements performed around the PRACLAY experiment.

6.7.3 Key results/achievement/deliverables

Praclay experiment

The main goal of the experiment is examining the impact of a large-scale thermal load on the Boom Clay. Such a thermal load leads to perturbations in the clay and can affect its performance as a host rock in the geological disposal concept for radioactive waste. The impact of the thermal load on the clay is examined and evaluated in the **Heater Test**. To overcome eventual future changes in the repository design and because it is not possible to simulate the time scale, the spatial scale and the boundary conditions that apply for a real repository, the test was designed to be as design-independent as possible and aims at imposing the most penalising thermo-hydromechanical (THM) conditions that are reasonably achievable.

The PRACLAY In-Situ Experiment comprises three tests: the Gallery&Crossing Test, the Seal Test and the Heater Test (**Figure 29**).

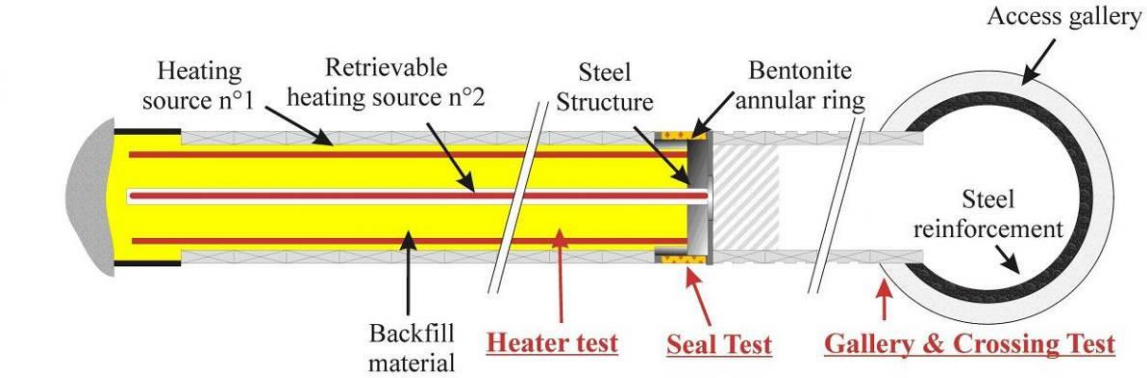


Figure 29: The PRACLAY In-Situ Experiment comprises three tests: the Gallery&Crossing Test, the Seal Test and the Heater Test

An intensive instrumentation network was installed around and inside the PRACLAY gallery in order to monitor the THM responses of Boom clay and interaction with the lining and the seal (**Figure 30**). The lining itself was equipped also with sensors to monitor the strain/stress and contact pressure during the experiment.

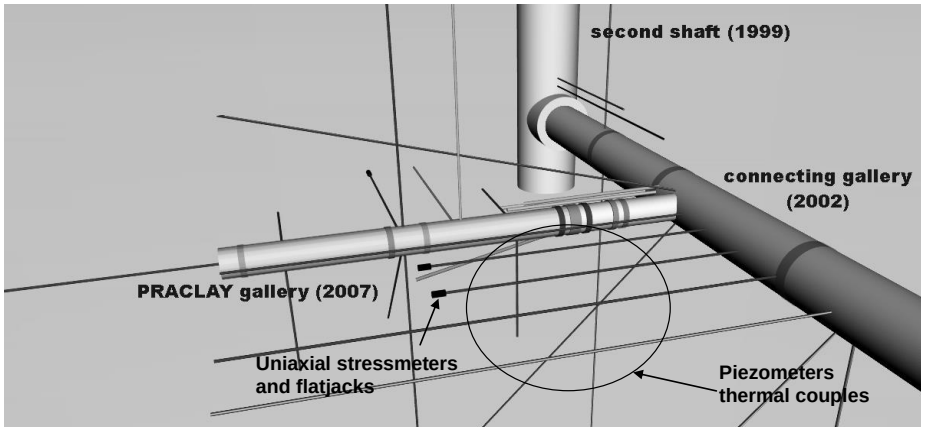
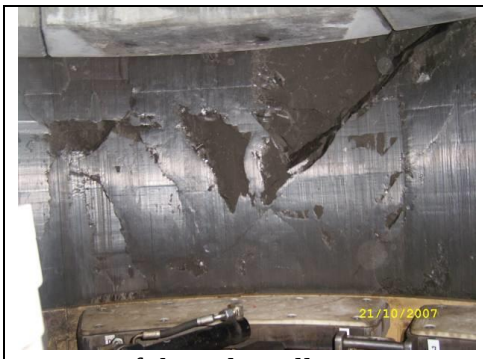


Figure 30: PRACLAY Heater Test with observation boreholes

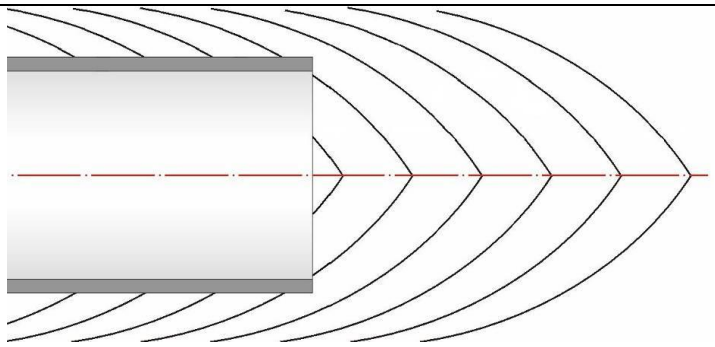
The design of the experiment, the geometry of gallery, gallery construction technique, experiment components , as well as in situ measurements/observation before, during and after excavation of Praclay gallery are given in the corresponding deliverable 11(D11/WP4.2- Large scale in-situ Praclay experiment results).

The Praclay gallery was excavated by tunnel machine. The observed fracture pattern is given in Figure 31.

The pore water pressure measured in different boreholes (next to the gallery at several horizontal distances and below the gallery) before/during/after excavation of praclay gallery is given in **Figure 32** . Due to the low permeability of the clay, undrained behaviour prevails in the short term and the volumetric deformations that result from the stress redistribution, directly causes changes in the pore water pressure. The different pore pressure variation measured at boreholes next to gallery and below gallery indicated the anisotropic behaviour of Boom clay and also anisotropic in situ stress.



Picture of the side wall



Observed fracture pattern

Figure 31: EDZ of Praclay gallery

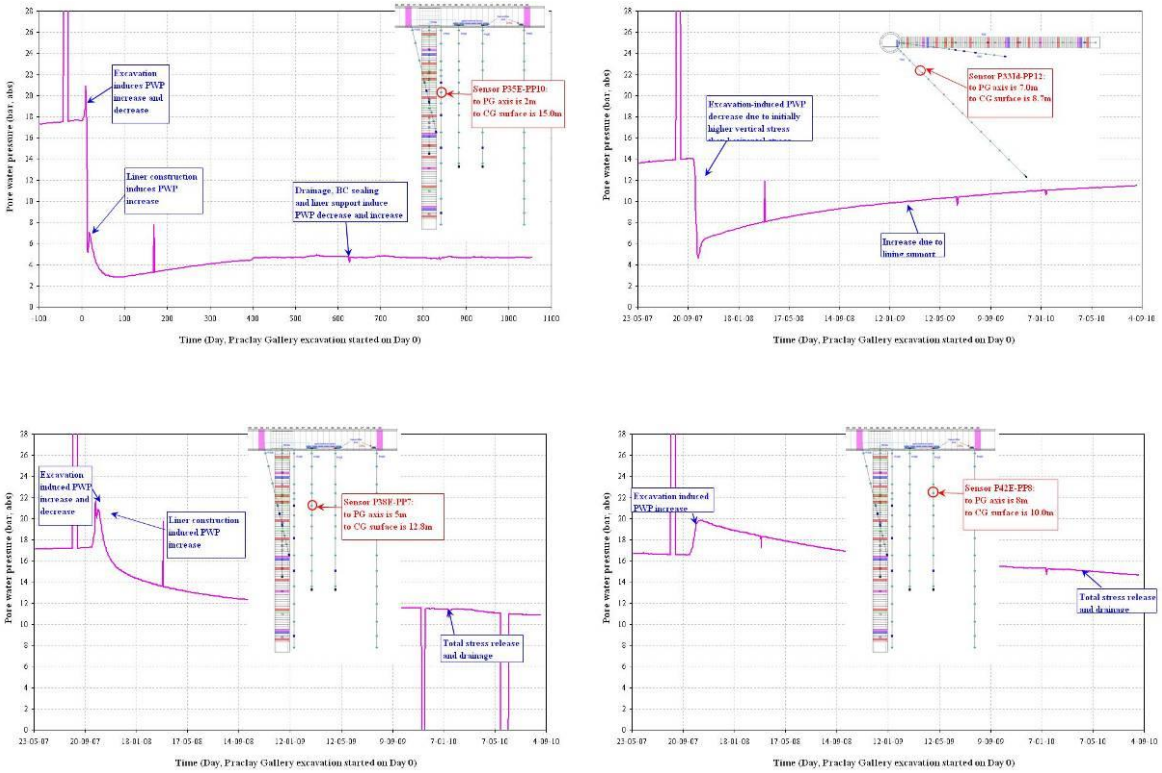


Figure 32. Pore water pressure measured in borehole P35E (top left), P33Id (top right), P38E (bottom left) and P42E (bottom right)

Finally, the convergence measured during excavation indicated that it is larger in the horizontal direction than in the vertical direction. This is consistent with the lab simulation test performed by EPFL.

The switching on of the heater depends on the hydration of the bentonite. The bentonite has to have reached a sufficiently high swelling pressure to assure the undrained boundary conditions at the intersection between the heated and non-heated part of the gallery. This switching on of the heater is expected to be for end of 2011.

Several measurements were carried out during and after the excavation of the PRACLAY gallery. They aimed to gain as much information as possible on the performance of the excavation technique, the behaviour of the Boom Clay and the impact of the excavation on the clay. This information was gained

through observations and measurements on the massif, the lining and the tunnelling machine. The results were in line with previous observations and confirm the highly coupled and anisotropic hydromechanical behaviour of the Boom Clay and known fracturing processes. These measurements provide valuable data for the validation of the constitutive models developed in the Timodaz project (WP5).

Ultrasonic monitoring of the PRACLAY gallery (ASC)

ASC's primary role in the TIMODAZ project involves the development of seismic processing techniques for assessing the characteristics and behaviour of the rock mass around the PRACLAY heater test using ultrasonic and acoustic data and to then apply these techniques to measurements from the PRACLAY experiment.

To this purpose, the strategy developed in the OMNIBUS project, based on the use of active and passive ultrasonic measurements to remotely monitor the rock barrier around excavations (e.g. access tunnels and deposition holes) was followed.

Microseismicity, acoustic emission (AE) and ultrasonic-survey technologies are scaled seismic investigations that provide remote non-destructive methods of examining the disturbance and damage evolution induced in the rock mass around an underground excavation, potentially caused by the operating conditions of a high-level radioactive waste repository (through mechanical, thermal and hydraulic stresses, and chemical and biological processes). Amplitude and velocity changes on the ray paths during ultrasonic surveys can be interpreted in terms of changes in the material property of the rock. Calculations using the velocities can determine the changes in dynamic moduli, Young's modulus and Poisson's ratio, to give direct indications of the properties of the rock through which the raypaths travel. Crack density and saturation can also be calculated to determine changes in crack properties in the damaged and disturbed zones. AE monitoring is a 'passive' technique similar to earthquake monitoring but on a much smaller distance scale (source dimension of millimetres) and higher frequency range. AEs occur on fractures in the rock when they are created or when they move. These technologies provide unique data for remotely characterising the host rock, allowing volumes of disturbance and damage to be delineated and quantified, and providing measurements for the calibration and validation of numerical models that predict the effects of the repositories' operating conditions.

These technologies have been used in the framework of the large scale PRACLAY experiment. AE recording and fully automated daily ultrasonic surveys are performed using monitoring array around Praclay gallery. The monitoring system consists of eighteen ultrasonic transmitters and receivers installed in three boreholes, quasi-parallel to the PRACLAY gallery.

During the first phase of the project a study was performed investigating published literature, finding the technique developed by Kachanov (1994) to be a simple and reliable method for the calculation of the full suite of crack density, aspect ratio and crack alignment parameters from elastic wave velocity data. Effective medium theory and poroelasticity are fundamental tools to calculate the cracked rock dry and wet (low and high frequency limits) elastic properties in terms of the crack density tensor, the solid grains and fluid elastic properties and the porosity. Inversions performed using Kachanov's code have been shown to be very stable and gave coherent results in terms of crack density and aperture evolution, mean crack distribution orientations and porosity evolutions.

An interface was developed during the first stages of the project to analyse measurements from acoustic monitoring and ultrasonic surveys recorded at the PRACLAY Experiment using ASC's commercial processing package InSite.

Daily ultrasonic surveys have been carried out on the south side of the PRACLAY gallery since September 2006, when the ultrasonic monitoring array was installed ahead of the excavation of the test gallery. Monitoring is still on-going. Ultrasonic surveys are used to actively examine the rock, providing a measurement of amplitude and velocity changes between transmitter-receiver pairs (Figure 33).

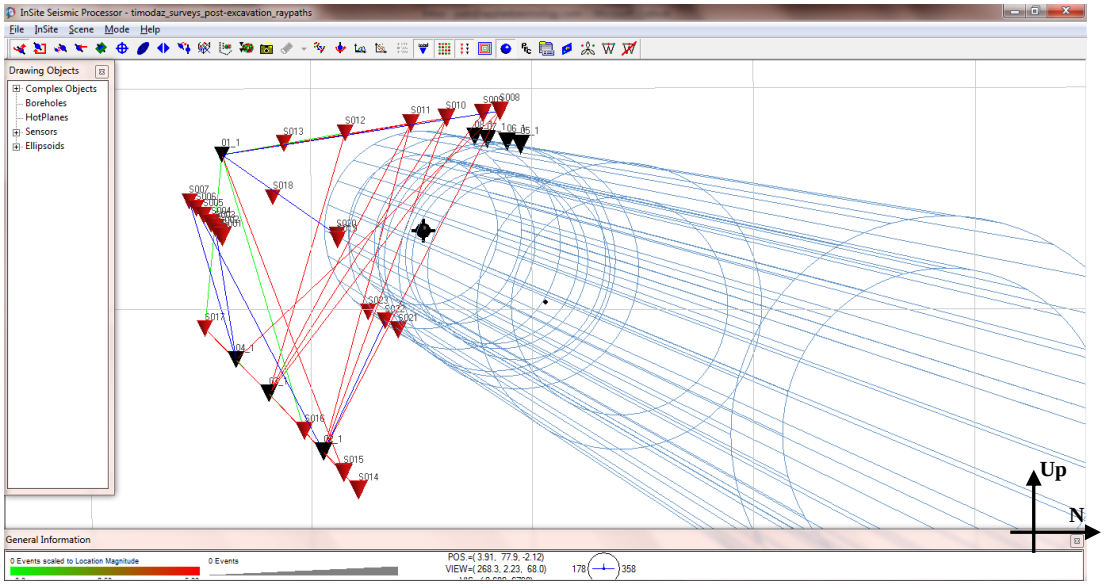


Figure 33: Layout of the pulsers (red) and receivers (black) used in the ultrasonic surveys performed for the monitoring of the PRACLAY gallery.

Processing of P-wave transmission velocities from daily ultrasonic surveys were performed around the PRACLAY gallery for the period between sep. 2006 and April 2010.

Different behavior patterns have been identified in terms of response to the stress changes induced by the excavation of the gallery: Raypaths with a pronounced decrease in transmission velocity, associated with crack damage development, during the gallery excavation. In all cases a sustained increase in transmission velocities is observed immediately after completion of the excavation, indicating a fast 'sealing/healing' of the crack damage induced during the excavation. The increase is in general followed by a steady state at transmission velocities above those observed following the setting of the monitoring instruments (**Figure 34**).

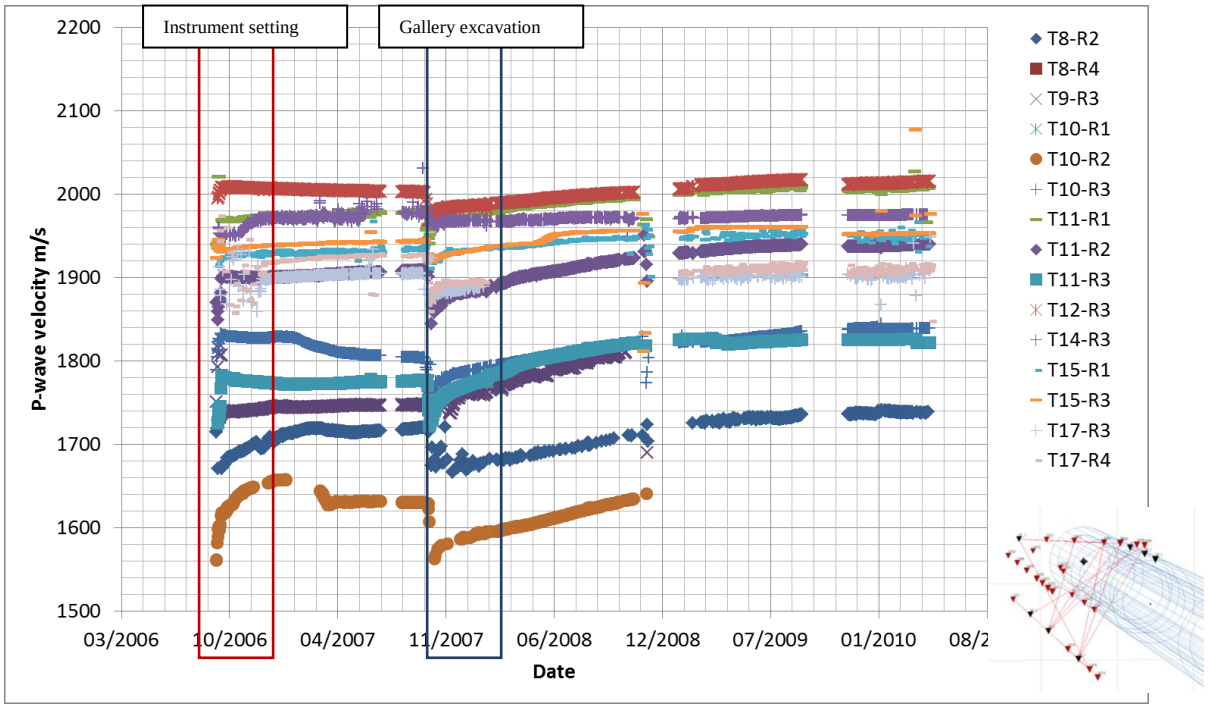


Figure 34: P-wave velocity along fifteen raypaths crossing different regions in the Boom Clay host rock neighbouring the PRACLAY test gallery (inset). These raypaths show micro-crack development induced by the excavation of the gallery in the surveyed volumes and directions.

A strong 3D anisotropy is observed during the complete monitoring period. The evolution of this anisotropy provides an image of the changes in the host rock fabric and fracture geometry induced by the excavation of the test tunnel. Relatively high transmission velocities are observed for shallow dipping raypaths (<30° dip measured from the horizontal), particularly in the direction of the excavated tunnel (approx. N100W). A secondary maximum is also observed at approximately 30° from the tunnel axis. A relative minimum in transmission velocity develops in the direction normal to the tunnel axis at a wider range of incidence angles. This minimum is observed in the period including and following the excavation of the gallery in November 2007. This relative minimum can be interpreted as an indication of the development of a fabric normal to the radial direction of the tunnel (**Figure 35**).

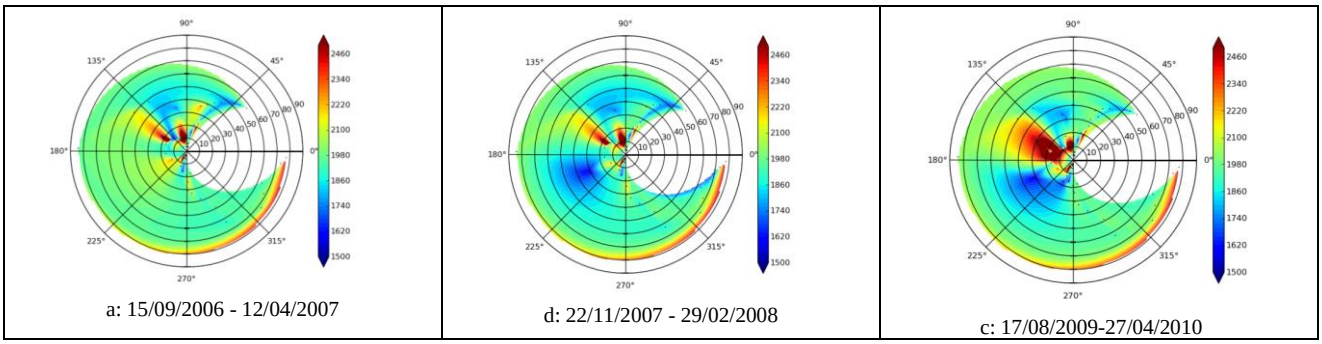


Figure 35: Stereographs showing the values of v_p with respect to azimuth and dip measured from ultrasonic daily surveys. Azimuths are shown in degrees towards West measured from North. Dip angles are measured from the horizontal. The orientation of the tunnel axis is approximately 100° West of North.

The results form part of the final report deliverable D12/WP4.2- Ultrasonic monitoring of the Praclay gallery.

6.7.4 Publications

International/national journal

- Li X.L., Bastiaens W., Van Marcke P., Verstricht J., Chen G., Weetjens E., "Design and development of large-scale in-situ PRACLAY heater test and horizontal high-level radioactive waste disposal gallery seal test in Belgian HADES" *Journal of Rock Mechanics and Geotechnical Engineering*, 2:2(2010), p. 103-110. ISSN 1674-7755

International /national conference

- Reyes-Montes, J.M., Pettitt, W.S. Haycox, J.R., Andrews, J. and R.P. Young. "Characterisation of rock mass crack damage using ultrasonic surveys". *Euradwaste 2008: Seventh European Commission Conference on the Management and Disposal of Radioactive Waste*. Luxembourg 20-22 October 2008.
- Reyes-Montes, J.M., Areias, L., Li, X.L., Pettitt, W.S. Haycox, J.R. and R.P. Young. "Ultrasonic Monitoring of the Excavation Damaged Zone in Boom Clay in the PRACLAY Experiment". *Impact of Thermo-Hydro-Mechanical-Chemical (THMC) processes on the safety of underground radioactive waste repositories: An international conference and workshop in the framework of the European Commission TIMODAZ and THERESA projects*. Luxembourg, 29th September – 1st October 2009
- Li Xiang-Ling, Bastiaens Wim, Weetjens Eef, Sillen Xavier, "The THM boundary conditions control in the design of the large scale in situ PRACLAYheater test" *Impact of Thermo-Hydro-Mechanical-Chemical (THMC) processes on the safety of underground radioactive waste repositories: An international conference and workshop in the framework of the European Commission TIMODAZ and THERESA projects*. Luxembourg, 29th September – 1st October 2009
- Li Xiang-ling, Bastiaens Wim, Van Marcke Philippe, Verstricht Jan, Chen Guang-jing, Weetjens Eef, Sillen Xavier, "Design and development of the large scale in-situ praclay heater test and horizontal HLW disposal gallery seal test in Belgian URL HADES" *International Symposium on Unsaturated Soil Mechanics and Deep Geological Nuclear Waste Disposal (UNSAT-WATE 2009), 24-28 August 2009, Shanghai, China.*
- Reyes-Montes, J.M., Areias, L., Li, X.L., Pettitt, W.S. Haycox, J.R. and R.P. Young. "Ultrasonic Monitoring of the Excavation Damaged Zone in Boom Clay in the PRACLAY Experiment". *to be published in the proceedings of the international conference and workshop in the framework of the European Commission TIMODAZ and THERESA projects*. Luxembourg, 29th September – 1st October 2009
- Li Xiang-Ling, Bastiaens Wim, Weetjens Eef, Sillen Xavier, "The THM boundary conditions control in the design of the large scale in situ PRACLAYheater test" *to be published in the proceedings of the international conference and workshop in the framework of the European Commission TIMODAZ and THERESA projects*. Luxembourg, 29th September – 1st October 2009
- Reyes-Montes, presentation of the work from WP 4.2 in The workshop on monitoring technologies, as part of the MoDeRn project, EC FP7 framework, 7-9 June 2010 at the Université de Technologie de Troyes, France.

6.8 WP 4.3 – Lining stability under thermal loading

6.8.1 Objectives of WP 4.3

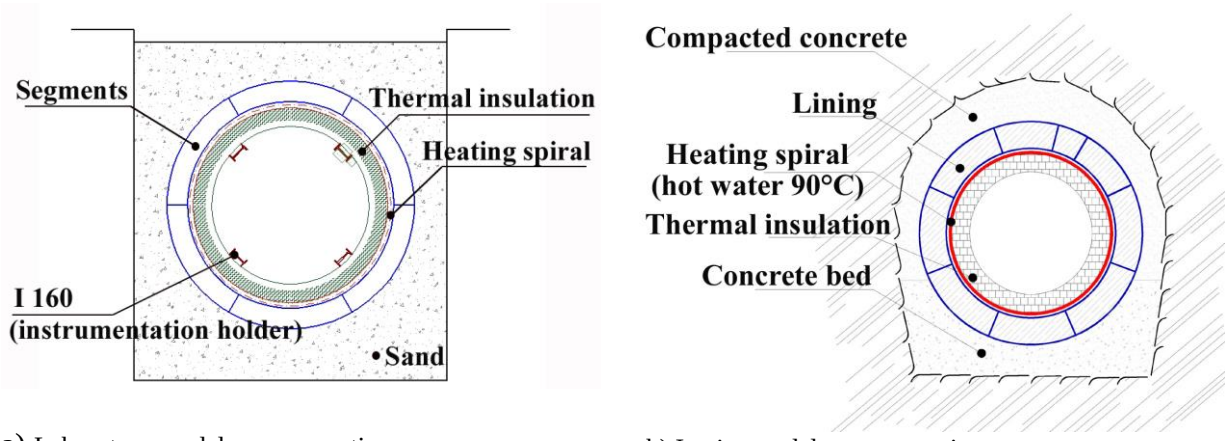
The overall objective of this workpackage is to study the influence of thermal impact on the stability of lining. This issue is particularly important in terms of operational safety when the retrievability of the radioactive waste is considered. Both laboratory test and in-situ test were performed.

6.8.2 Participants of WP 4.3

Only CTU-CEG participated this workpackage.

6.8.3 Key results/achievement/deliverables

Two physical models have been built to study the stability of the tunnel lining under long term thermal load. One is situated in the underground silo of the laboratory of the Centre of Experimental Geotechnics (CEG) in Prague (**Figure 36** a), the other in the underground laboratory of the Josef UEF near Dobříš (**Figure 36** b). Each of the physical models investigates a different extreme case in terms of tunnel lining loading.



a) Laboratory model – cross-section

b) In-situ model – cross-section

Figure 36: physical models to study the stability of the lining under long term thermal load

The laboratory model has been designed to allow lining deformation in the direction towards the surrounding environment (compacted sand) during thermal loading, the principal monitored parameters include temperature and deformation in such case.

The in-situ physical model aimed at, conversely, the study of limit loading. The model has been assembled in a rock continuum (hard tuffitic rocks). The space between the circular lining and the rock is backfilled with concrete, the deformation towards the surrounding environment is in principle constrained. The principal monitored parameters in this case include temperature and stress.

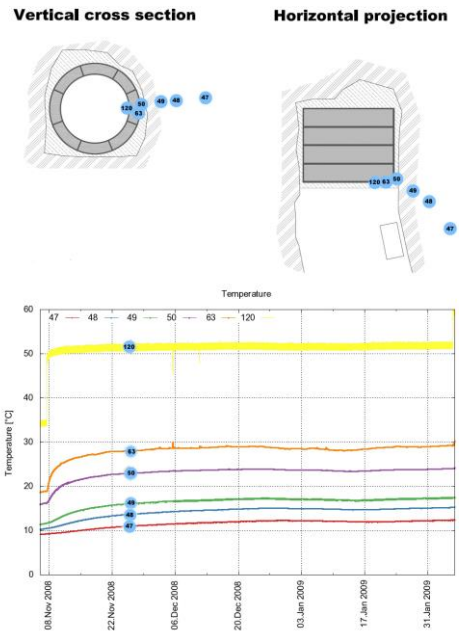
The in situ experiment has been divided into 2 testing phases (phases 01 and 02) and 6 loading phases:

a) Phase 01 – measurement during in-situ model assembly
b) Phase 02 – measurement during testing of the heating system
c) Phase 1 – 1st loading step (10°C – 40°C)
d) Phase 2 – 2nd loading step (40°C – 60°C)
e) Phase 3 – 3rd loading step (60°C – 70°C)
f) Phase 4 – 4th loading step (70°C – 80°C)
g) Phase 5 – 5th loading step (80°C – 90°C)
h) Phase 6 – 6th loading step (heater switch off)

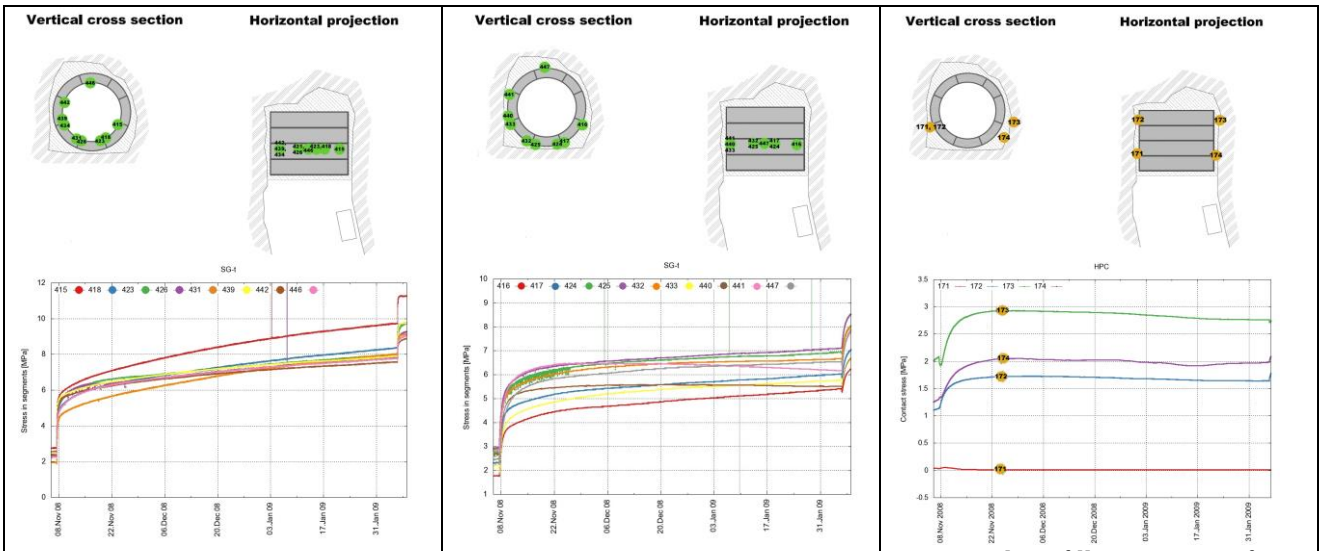
The heating phase was launched on 30th October 2008. The experiment was terminated in August 2010. The maximum temperature of the inner surface of the lining reached 85°C. The measured stress within the concrete segments was very inhomogeneous. Ordinary levels of stress inside the lining were in the range 0 to 16 MPa. However measured maximum stress reached to 24 MPa. Of the 24 vibrating wire strain gauges installed inside the segments (near the maximum heat loading location) more than 80%

failed. It should be noted that during the long-term experiments with thermal loading greater attention must be devoted to instrumentation; it will be essential to combine a number of different measuring systems.

The experiment provided a valuable data base for the liner stability evaluation. However, some aspects, especially the magnitude of the measured stress values and short-term stress behaviour after a temperature change need to be verified by means of further research. **Figure 37** shows the test results during the 2nd phase of the test: the evolution of the stress at intrados and extrados as well as the contact stress with the temperature change.



Temperature



stress at intrados | stress at extrados | Stress at liner/filler contract surface

Figure 37 : Temperature and stress evolution during the 2nd heating phase

The results of the both laboratory and in situ tests were reported in [D09/WP4.3- Lining stability under thermal load].

6.8.4 Publications

International journal

- Svoboda, Vašíček, " Long-term lining performance - Civil engineering problem of potential retrieval of buried spent nuclear fuel" *Nuclear Engineering and Design (Elsevier journal)*, 2010, accepted article, on-line already available

International /national conference

- Jaroslav Pacovský, Jiří Svoboda, Radek Vašíček, "Lining Stability Under Thermal Load: In Situ Experiment" *Impact of Thermo-Hydro-Mechanical-Chemical (THMC) processes on the safety of underground radioactive waste repositories: An international conference and workshop in the framework of the European Commission TIMODAZ and THERESA projects. Luxembourg, 29th September – 1st October 2009*
- Jaroslav Pacovský, Jiří Svoboda, Radek Vašíček, "Lining Stability Under Thermal Load: laboratory Experiment" *Impact of Thermo-Hydro-Mechanical-Chemical (THMC) processes on the safety of underground radioactive waste repositories: An international conference and workshop in the framework of the European Commission TIMODAZ and THERESA projects. Luxembourg, 29th September – 1st October 2009*
- Jaroslav Pacovský, " TIMODAZ: Lining Stability under Thermal Load", Fourteenth International Conference on Environmental Degradation of Materials in Nuclear Power Systems 2009, Virginia Beach, USA, 23-27.8.2009
- Svoboda, Vašíček" Potential Retrieval of Buried Spent Nuclear Fuel and Civil Engineering Aspects", Nuclear Energy for New Europe, Bled, Slovenia, 14-17.9.2009
- Pacovský, Vašíček "The effects of long-term thermal load on the stability of the lining of a deep underground repository" Ravage of the Planet II, Gordon´s Bay, SA, 15-17.12.2009
- Pacovský, Svoboda, Vašíček " The Effects of Long-term Thermal Load on Lining Stability" IS-Shanghai 2010: International Symposium on Geomechanics and Geotechnics: From Micro to Macro, Shanghai, China, 10-12.10.2010
- Vašíček, Svoboda, Levorová " Lining Response to Thermal Loading – Experimental Study", WTC 2011, Helsinki, Finland, 21.-26.5.2011, abstract accepted
- Jaroslav Pacovský, Jiří Svoboda, Radek Vašíček, "Lining Stability Under Thermal Load: In Situ Experiment" to be published in the international conference and workshop in the framework of the European Commission TIMODAZ and THERESA projects. Luxembourg, 29th September – 1st October 2009
- Jaroslav Pacovský, Jiří Svoboda, Radek Vašíček, "Lining Stability Under Thermal Load: laboratory Experiment" to be published in the international conference and workshop in the framework of the European Commission TIMODAZ and THERESA projects. Luxembourg, 29th September – 1st October 2009

6.9 WP 5 – modeling and benchmarks

6.9.1 Objectives of WP 5

WP5 comprises two subworkpackages : WP 5.1 and WP5.2.

WP5.1 aims to develop numerical tools allowing simulation of the THMC process around a repository at time and repository scale. These numerical tools are essential to address the following relevant questions:

- What is the expected evolution of the clay around a disposal system for heat-emitting waste during the thermal period?
- What are the main uncertainties about the EDZ+TDZ evolution and how can these uncertainties be dealt with?

- What the ultimate thermal limits of the clay could be in the context of the long term performance of the repository system

WP5.2 consists in a set of numerical Benchmarks with the help of developed numerical tools developed in WP5.1. The aim of the workpackage is to assess the performance of coupled THM analysis, using different codes, of proposed laboratory tests and in situ tests (available and prospective), with a main focus on the development and evolution of the DZ. The modelling work together with the results of the lab and the in-situ tests should give clear indication on the evolution of the DZ with time: What are the risks of fracturation? What are the favourable and the unfavourable effects of the thermal load on sealing? What are the THMC governing processes and parameters at repository time and spatial scale?

6.9.2 Participants of WP 5

11 participants: EURIDICE, NAGRA, SCK•CEN, GRS, NRG, CIMNE, EPFL, ULG, UJF, ENPC, ITASCA

6.9.3 Key results/achievement/deliverables

6.9.3.1 WP5.1- Constitutive models development

Three tasks are planned in the WP5.1 :

- Task 1: THM coupling process modelling
- Task 2: chemical process and THMC coupling processes
- Task 3: sealing process modelling

Task 1: THM coupling

Initially planned work: *Thermo-Hydro-Mechanical constitutive models will be further advanced and numerical codes will be developed and improve…. The major developments will consist of:*

- *Constitutive modelling of the clay rocks, in a continuum framework to incorporate heat changes and transfers, moisture transfer, mechanical stress – strain evolution (including the development, evolution of micro cracks and the viscous – creep effects), and their interaction, especially in relation with thermal effects.*
- *Utilisation of local 2nd gradient models in order to provide objective descriptions of the behaviour in the post-localization regime. In particular, it will be possible to objectively describe the shear band thickness, which governs the interaction with other emerging or existing shear bands and with the water transfer properties.*
- *Extension of THM coupling in an unsaturated set to the 2nd gradient model.*
- *Modelling of the transition from the onset of strain localization up to rupture (fracturing), with related effects on permeability and coupled effects.*
- *Development of remeshing techniques in the related numerical codes when necessary.*

The most important developments are dedicated to modelling the thermo-hydro-mechanical behaviour of argillaceous rocks (Boom Clay, Opalinus Clay and Callovo-Oxfordian Clay). Two finite element codes were widely used and improved:

- the Code_Bright software, developed by UPC and used by UPC, GRS and Euridice
- the LAGAMINE code, developed by ULg and used by ULg, UJF, EPFL and Euridice

On the other hand, ITASCA has used its own code PFC3D, as well as ENPC with θ-Stock.

Some mechanical constitutive models have been developed or improved:

- EPFL has developed the thermoplastic model ACMEG-T. It is based on a non linear thermo-hypo-elasticity, an isotropic yield mechanism affected by temperature changes and a CamClay based deviatoric mechanism with friction angle temperature dependent, and a progressive transition from elastic to elastoplastic behaviour.
- ULg has developed a thermoplastic model based on the Sultan and Delage proposition for the temperature effect. It is a cap model with a Drucker – Prager – Van Eekelen deviatoric mechanism and a modified CamClay based isotropic mechanism. A thermal yield limit models the generation of volumetric thermal strain while a loading yield limit represents the Preconsolidation pressure decrease with temperature.
- An anisotropic elastoplastic model has been developed jointly by ULg and UJF . Full anisotropic linear elasticity is postulated, and the Drucker – Prager isotropic yield model with non linear hardening / softening is taken into account.
- ENPC has developed a thermo-hydro-mechanical damage model, formulated in independent state variables, with a second order damage tensor. Damage growth is controlled by an associated flow rule, depending on tensile strains. The conductivities of liquid and gas are influenced by cracking.
- CIMNE has developed a damage plasticity model which tackles the behaviour of hard clays and mudstones within a framework developed for bonded soils. A stress and strain partition is postulated between the matrix and the bonds. Different soil or rock constitutive models may be activated for the matrix behaviour, while the Carol damage model is used for the bond model. The model is extended for taking into account the hydraulic and thermal effects and the elastic anisotropy.

The fluid flow models have also been improved:

- ULg, CIMNE and Euridice have introduced anisotropic intrinsic permeability in their fluid flow and thermal conductivity in their heat flow models
- ULg and CIMNE have developed models linking permeability evolution to mechanical strain. The cubic law is considered for modelling flow in micro fractures. Micro fractures are identified as the tensile part of the strain gradient, giving so an orthotropic permeability tensor. A crack spacing is postulated, which allows to localise strains and crack opening in a reduced number of cracks, and so to model permeability changes of some orders of magnitude.

Eventually, the excavated damage zone may exhibit strain localisation, a process whose numerical simulation with classical models is dependent on the mesh size. In order to avoid such drawback, UJF followed by ULg has developed second grade models, which introduce an internal length in the mechanical models. UJF has extended this formulation to coupled THM processes.

Task 2: Sealing processes

Initially planned work: *Modelling of sealing processes under thermal load based on PFC3D (discontinuum) code will be performed by ITASCA. The work will consist in:*
- Improve the current numerical models in order to reproduce the short and long term behaviours of each clay rock.
- Model the fracturing and the sealing process at ambient temperature and study the impact of temperature on their evolution.
- Assess the effect of discrete fractures and fracture connectivity on the effective axial hydraulic properties of the DZ.

Itasca has developed with its code PFC2D a viscoplastic model dedicated to sealing process modelling in Opalinus clay. PFC2D is a discrete element code. Material mechanical behaviour is modelled thanks to spherical particle interaction: contact, friction, elastic deformation, damping, etc. A creep interaction model has been implemented, based on a power law, written with a threshold governing the sign of the strain and so allowing a kind of healing effect.

Task 3: Chemical processes

Initially planned work: *SCK•CEN will perform some static thermodynamic calculations to have an idea on the combined effect of temperature and pore water chemistry on the mineralogy and to help evaluating the results of WP3-d.*

CIMNE will perform the coupled THMC analysis, using CODE_BRIGHT, to examine the possible role of geochemical variables on the development and evolution of the DZ. Attention will be especially paid to osmotic flow, salt dissolution and precipitation and thermal effects.

SCK-CEN has performed equilibrium modelling using the geochemical computer code GWB, to scope the effect of temperature increase on pore water chemistry of Boom clay. Modelling takes into account the minerals measured in mineralogy composition of Boom clay, including reactive minerals such as calcite, siderite, pyrite, quartz … and cation exchange mechanism. The potential influence of natural organic matter as a source of CO2 (g) was also assessed. The results of equilibrium modelling indicate, as a result of a temperature increase, an increase of P_{CO_2} , a decrease of pore water pH and a general increase of major cation concentrations. Anion concentrations are not impacted by temperature to significant extent. Modeling indicates that the redox potential is not affected by temperature. Important minerals in the Boom Clay are stable under the expected range of temperature.

Code_Bright, developed by CIMNE, allows also taking into account the geochemical evolution, coupled mainly fluid flow, temperature and mechanics. Balance equation are written for water and for all conservative (non reactive) species. The flux of water and of species has an advective and /or a non-advective component. The Darcy's law is modified to model the osmotic pressure gradient, which is related to the water activity.

General conclusions from WP 5.1 activities

Most of the planned developments have been achieved during the TIMODAZ project duration, allowing modelling numerous lab and in situ experiments (see Deliverable D13 – Work package 5.2). Only some aspects related to strain localisation modelling (transition from localised behaviour to rupture and the subsequent remeshing) were not possible to develop. On the other hand, it appeared during the project that anisotropy of the rock in the three concerned underground laboratories, at Mol, Mont Terri and Bure, could be of major concern considering the analysis and the numerical simulation of in situ experiments. Following this point, a number of unexpected developments were achieved: an anisotropic elastoplastic mechanical model, an anisotropic fluid and heat flow model and an orthotropic strain coupled permeability model. This has asked an important additional effort, but has given first interesting results. The Timodaz teams suggest hardly expanding largely the work dedicated to anisotropy during the forthcoming years.

Detailed description of developed models and their validation are given D10/WP5.1 - Constitutive models development.

6.9.3.2 WP5.2- Benchmarks

The three benchmarks are performed within WP5.2 :

- Benchmark 1: laboratory experiments modelling performed within WP3.3.
  - Benchmark 1.1 : Hollow cylinder test on Boom clay
  - Benchmark 1.2 : Hollow cylinder test on Opalinus clay
  - Benchmark 1.3 : Hollow cylinder test on COX
- Benchmark 2: small-scale in-situ experiments modelling
  - Benchmark 2.1 : in-situ Mont Terri dilatometer experiment.
  - Benchmark 2.2 : in-situ ATLAS experiment (Mol URL).
- Benchmark 3 : Blind prediction of the PRACLAY experiment

The modelling work focuses on the following topics:

- Investigation of the thermal impact on EDZ
- Investigation of possible additional damage due to thermal load
- Transition between brittle and visco-plastic behaviour due to thermal loading
- Difference between continuum modelling and discrete element modelling

Different codes are evaluated by participation in Benchmark exercises for modelling of THM processes in clays. The benchmarks allow to assess the influence of the constitutive laws on the long term and large scale predictions, and to see if different modelling teams using different codes and/or constitutive laws can obtain similar predictions.

A synthesis of the numerical simulations of all these benchmark was given in deliverable 13. Full length description of benchmark results are reported in 5 extensive annexes. The main report of deliverable 13 and associated annexes are given in the public area of portal TIMODAZ: D13:WP5.2- simulations of lab and in-situ tests (main report and annexes), where the reader can find any detail of interest.

Main conclusions from WP5.2

The initial work forecasts have been more or less followed.

The numerical simulation of small scale lab hollow cylinder tests has been done with different mechanical elastoplastic models (Drucker-Prager, Mohr-Coulomb, ACMEG-T, different hardening / softening scheme). During the project, it appeared that hydromechanical anisotropy and permeability evolution with strain were important topics. New developments have been achieved (see deliverable D10) and used in the numerical simulations: mechanical anisotropy and permeability changes are crucial for a good simulation of the experiments. Moreover, micro tomography of samples before, during and after tests by EPFL, suggest some strain localisation. So numerical simulation of strain localisation has been achieved using second grade models and using advanced constitutive models including anisotropy. They have shown that the observed strain pattern is partly reproduced.

Small scale ATLAS in situ heating test modelling shows again the anisotropy importance, and especially that mechanical anisotropy may explains some observed specificities of pore pressure evolution, that where nor understood in the preceding. This implies that 3D models are needed. Non linear elastic mechanical behaviour has also been checked.

The Mont Terri in situ test has put in evidence the mechanically induced permeability and its anisotropy evolution. Further progresses in these experiment modelling will require to take into account strain

localisation and 3D effects.

The Praclay large scale in situ test was the last analysed experiment. Its complexity is much larger than the other experiments ones, as it includes a liner – host rock interaction, a gallery crossing effect and 3D aspects. A number of progresses obtained in the preceding exercises have been valorised in this simulation. It has been shown the 2D plane strain or axisymetric simulations only partly cover the complexity and that only a 3D anisotropic simulation may allow a full understanding of the tests.

A comparison of some used constitutive models and set of parameters to experimental results show a partial agreement. Comparing the stress paths with the hollow cylinder and Praclay large scale test, some agreement exist but new lab experiments would give some additional information that will be needed for next researches.

Some major conclusions of the numerical simulations are the importance of:

- The initial and induced anisotropy, including stress anisotropy, elastic anisotropy, plastic anisotropy, permeability anisotropy and thermal conductivity anisotropy.
- The cohesion evolution induced by plasticity, damage and thermal loading.
- The permeability induced by strain in the damage zone.

We hope that these themes will be the subject of future funded collaborative projects.

6.9.4 Publications

International Journals with reviewing committee

- Gens A., Garitte B., Olivella S. and Vaunat J. 2009. Applications of multiphysical geomechanics in underground nuclear waste storage. European Journal of Environmental and Civil Engineering. Vol.13-No 7-8/2009. (Eds: Félix Darve and Marco di Prisco), pp 937-962.
- C. Arson, B. Gatmiri, 2009. Numerical study of a thermo-hydro-mechanical model for unsaturated porous media, *Annals of Solid and Structural Mechanics*, accepted with revision, in second review
- C. Arson, B. Gatmiri, 2009. A mixed damage model for unsaturated porous media, *Comptes-Rendus de l'Académie des Sciences de Paris, section Mécanique*, vol. 337, pp.68–74
- C. Arson, B. Gatmiri, 2008. On damage modelling in unsaturated clay rocks, *Physics and Chemistry of the Earth*, vol.33, pp. S407–S415
- C. Arson, B. Gatmiri, 2008, "Excavation damage in unsaturated porous media", *Key Engineering Materials*, Advances in Fracture and Damage Mechanics VII, vol.385-387, pp.137-140.
- C. Arson, B. Gatmiri, 2008, "On damage modelling in unsaturated clay rocks", *Physics and Chemistry of the Earth, JPCE 1618, DOI: 10.1016/j.pce.2008.10.006.*
- B. Gatmiri, C. Arson, 2008, "Θ-STOCK, a powerful tool for thermohydromechanical behaviour and damage modelling of unsaturated porous media", *Computers and Geotechnics, special issue: "Unsaturated Soils: Models, Algorithms and Applications", 35, pp.890-915*
- C. Arson, B. Gatmiri, "A mixed damage model for unsaturated porous media", submitted for publication in *Comptes-rendus de l'Académie des Sciences, section Mécanique*
- C. Arson, B. Gatmiri, 2010. Numerical Study of Damage in Unsaturated Geological and Engineered Barriers, *Physics and Chemistry of the Earth*, submitted
- C. Arson, B. Gatmiri, 2010. Thermo-Hydro-Mechanical Modeling of Damage in Unsaturated Porous Media, *International Journal for Numerical and Analytical Methods in Geomechanics*, submitted
- C. Arson, B. Gatmiri, 2010. Numerical study of a thermo-hydro-mechanical model for

unsaturated porous media, *Annals of Solid and Structural Mechanics*, vol.1, n.2, pp. 59-78
- Levasseur S., Charlier R., Frieg B., Collin F. – Hydro-mechanical modelling of the Excavation Damaged Zone around an underground excavation at Mont Terri Rock Laboratory – *International Journal of Rock Mechanics and Mining Sciences*, **47**, pp. 414-425, 2010.
- Gerard P., Léonard A., Masekanya J.P., Charlier R., Collin F. – Study of the soil-atmosphere moisture exchanges through convective drying tests in anisothermal conditions – *International Journal for Numerical and Analytical Methods in Geomechanics*, **34**, pp.1297-1320, 2010.
- Collin F., Levasseur S., Chambon R. – Numerical post failure methods in multiphysical problems – *Revue Européenne de Génie Civil*, **7-8**, pp. 983-1004, 2009.
- Charlier R., Dizier A., Laloui L., Collin F. – Multi-physical processes in geomechanics – an introduction to constitutive modelling and coupling aspects – *Revue Européenne de Génie Civil*, **7-8**, pp. 803-830, 2009.
- Failure in multiphase geomaterials, European Journal of Environmental and Civil Engineering, Laloui L., Collin F. and De Gennaro V. (Guest Editors), Hermes Sciences ISBN: 978-2-7462-2534-3, 2009.
- Levasseur S., Collin F., Charlier R., Kondo D. – On a class of micromechanical damage models with initial stresses for geomaterials – *Mechanics Research Communications*, **37**, pp. 38-41, 2010.
- Sieffert Y., Al Holo S., Chambon R. (2009) - Loss of uniqueness of numerical solutions of the borehole problem modelled with enhanced media, International Journal of Solids and Structures, 46 (17), 3173–3197.

Proceedings of international/national conferences

- C. Arson, B. Gatmiri, 2008, "Outline of the modelling of the excavated damaged zone in geological barriers", Proc. *First European Conference on Unsaturated Soils, Durham, United Kingdom, 2-4 July 2008*, CRC Press, eds: D.G. Toll, C.E. Augarde, D. Gallipoli, S.J. Wheeler, pp.695-701.
- Sieffert Y., Collin F., Chambon R. (2007) - Objectivité de la solution d'un problème d'excavation d'une cavité, 18ème Congrès Français de Mécanique, Grenoble, 27 - 31 août 2007, 6p (CDROM).
- Charlier R., Chambon R., Li X.-L., Dizier A., Sieffert Y., Collin F., Levasseur S. (2008) - Modelling the Excavated Damage Zone around an underground gallery – Coupling mechanical, thermal and hydraulical aspects, Euradwaste 08, Luxembourg.
- Dizier A., Collin F., Garitte B., François B., Chen G.J., Sieffert Y., Labiouse V., Charlier R., Chambon R. (2009) - Thermo-hydro-mechanical modelling of hollow cylinder laboratory experiments on Boom Clay. Proceedings of the EC-TIMODAZ-THERESA THMC Conference, Luxembourg.
- Levasseur S., Bésuelle P., Collin F., Chambon R., Charlier R., Viggiani G. (2009) - EDZ in clayey rocks: which effect on permeability? Proceedings of the EC-TIMODAZ-THERESA THMC conference, Luxembourg.
- Levasseur S., Bésuelle P., Collin F., Chambon R., Charlier R., Viggiani G. (2010) - EDZ and Permeability in Clayey Rocks, International Meeting on Clays in Natural & Engineered Barriers for Radioactive Waste Confinement (abstract submitted in September 2009).
- Benoit Garitte, Xavier Sillen, X.L. Li, Gilles Armand, Jean Vaunat and Antonio Gens " Comparative study of three in-situ heating tests in anisotropic media: the HE-D, TER and ATLAS experiments" Proceedings of the EC-TIMODAZ-THERESA THMC conference, Luxembourg.

- Gens A., Garitte B., Vaunat J. 2008. Modelling the Response of Argillaceous Rocks in Underground Excavations. Proceedings of the 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG), pp 1197-1209.
- Garitte B., Vaunat J. and Gens A. 2008. In situ hydraulic response of low permeable anisotropic materials to thermal loading. 19th ALERT workshop.
- Garitte B., Gens A., Vaunat J. and Armand G. 2009. Hydraulic Response to a Shaft Excavation in Callovo-Oxfordian Clay. Proceedings of Int. Conf. on Computational Methods for Coupled Problems in Science and Engineering COUPLED PROBLEMS 2009 (B. Schrefler , E. Oñate and M. Papadrakakis, Eds) CIMNE, Barcelona, 2009.
- Garitte B., Vaunat J. and Gens A. 2009. Thermo-Hydro-Mechanical Response of an Argillaceous Rock: Experimental Results and Modelling. Proceedings of X International Conference on Computational Plasticity COMPLAS X (E. Oñate and D. R. J. Owen, Eds) CIMNE, Barcelona, 2009
- Vaunat J., Garitte B. and Gens A. 2009. Modelling of a Deep Excavation in a Stiff Clay. Proceedings of X International Conference on Computational Plasticity COMPLAS X (E. Oñate and D. R. J. Owen, Eds) CIMNE, Barcelona, 2009
- Armand G., Garitte B., Conil N., 2009. Response of the Callovo-Oxfordian Clay-Stone to Heating at the Meuse Haute-Marne URL. Proceedings of 8th Euro Conference of Rock Physics & Geomechanics.
- Garitte B., Vaunat J., Gens A. and Vietor T., 2009. Class A prediction of a Mine-By test in an overconsolidated mudstone. EURO:TUN 2009 2nd International Conference on Computational Methods in Tunnelling (Aedificatio Publishers, 1-4).
- S. Levasseur, F. Collin, B. Frieg & R. Charlier – Hydro-mechanichal modelling of damage due to underground excavation in indurated clay – PROCEEDINGS OF THE 1st INTERNATIONAL SYMPOSIUM ON COMPUTATIONAL GEOMECHANICS (COMGEO I), Juan -les- Pins, France, 29 April -1 May, 2009, pp. 503-512, 2009.
- S. Levasseur, F. Collin, B. Frieg, R. Charlier – Damage around tunnels in indurated clay: hydro-mechanical modelling aspects – Proc EC-TIMODAZ-THERESA THMC conference, 5 p., Luxembourg (L), 29 Sep. – 01 Oct. 2009.
- M. Mozayan, C. Arson, B. Gatmiri, 2010. Thermal damage in unsaturated geomaterials, Fifth International Conference on Unsaturated Soils, Barcelona, Spain, 6-8 September 2010, 6 pages
- M. Mozayan, C. Arson, B. Gatmiri, 2010. Study of tensorial damage in a porous geomaterial, 7th European Conference on Numerical Methods in Geotechnical Engineering, Trondheim, Norway, 2-4 June 2010, 6 pages.
- C. Arson, B. Gatmiri, 2009. Numerical study of a new THM damage model for unsaturated geomaterials, 4th Asia-Pacific Conference on Unsaturated Soils, New-Castle, Australia, 23-25 November, 2009, 6 pages, accepted
- C. Arson, B. Gatmiri, 2009. Mechanical validation of a damage model for non isothermal unsaturated porous geomaterials, Conference on the Impact of the Thermo-Hydro-Mechanical-Chemical Processes on the safety of underground repositories, Luxembourg, 29th September 2009, 5 pages,
- C. Arson, B. Gatmiri, 2009. Damage in unsaturated porous media: theory, algorithm and numerical application, in Poromechanics IV, Proceedings of the 4th Biot Conference on Poromechanics, Columbia University, New-York, USA, 8 - 10 June, 2009, Ling, Smyth and Betti eds, DESTech Publications, p. 214-219
- C. Arson, B. Gatmiri, 2009. Parametric study on the performance of a THM damage model for unsaturated porous media, 1st International Symposium on Computational Geomechanics, Juan-les-Pins, France, 29 April - 1st May 2009, pp. 553-562
- C. Arson, B. Gatmiri, 2008. Outline of the modelling of the excavated damaged zone in geological barriers, First European Conference on Unsaturated Soils, Durham, United Kingdom,

2 - 4 July 2008, Unsaturated Soils, Advances in Geo-Engineering, CRC Press, eds: D.G. Toll, C.E. Augarde, D. Gallipoli, S.J. Wheeler, pp. 695-701

- M. Mozayan, C. Arson, B. Gatmiri, 2010. Thermal damage in unsaturated geomaterials, Fifth International Conference on Unsaturated Soils, Barcelona, Spain, 6-8 September 2010, 6 pages
- M. Mozayan, C. Arson, B. Gatmiri, 2010. Study of tensorial damage in a porous geomaterial, 7th European Conference on Numerical Methods in Geotechnical Engineering, Trondheim, Norway, 2-4 June 2010, 6 pages
- C. Arson, B. Gatmiri, 2009. Mechanical validation of a damage model for non isothermal unsaturated porous geomaterials, Conference on the Impact of the Thermo-Hydro-Mechanical-Chemical Processes on the safety of underground repositories, Luxembourg, 29th September 2009, 5 pages, accepted
- J. Vaunat, A. Gens, R. de Vasconcelos & X.L. Li "Analysis of the excavation of a deep drift in a tertiary clay", proceedings of The Second International Symposium on Computational Geomechanics (ComGeo II) will take place at the Hotel Croatia, Cavtat-Dubrovnik, Croatia, 27-29 April, 2011.
- L. Laloui, S. Leroueil, S. Chalindar "Thermo-viscoplastic 'consistency' modelling of clays", Alert Workshop, Session 3: Time dependent processes in geomechanics, Aussois, 10th of October 2007.
- Dizier A., Collin F., Garitte B., François B., Chen G.J., Sieffert Y., Labiouse V., Charlier R., Chambon R. (2009) - Thermo-hydro-mechanical modelling of hollow cylinder laboratory experiments on Boom Clay. to be published in the proceedings of the EC-TIMODAZ-THERESA THMC Conference, Luxembourg.
- Levasseur S., Bésuelle P., Collin F., Chambon R., Charlier R., Viggiani G. (2009) - EDZ in clayey rocks: which effect on permeability? to be published in the Proceedings of the EC-TIMODAZ-THERESA THMC conference, Luxembourg.
- Benoit Garitte, Xavier Sillen, X.L. Li, Gilles Armand, Jean Vaunat and Antonio Gens " Comparative study of three in-situ heating tests in anisotropic media: the HE-D, TER and ATLAS experiments", to be published in the proceedings of the EC-TIMODAZ-THERESA THMC conference, Luxembourg.
- S. Levasseur, F. Collin, B. Frieg, R. Charlier "Damage around tunnels in indurated clay: hydro-mechanical modelling aspects" to be published in the proceedings of the EC-TIMODAZ-THERESA THMC conference, Luxembourg.
- S. Levasseur, P. Bésuelle, F. Collin, R. Chambon, R. Charlier, C. Viggiani – EDZ and Permeability in Clayey Rocks – Proc. 4th International Meeting ANDRA (Nantes), 2p, Avril 2010.
- Garitte B., Vaunat, J., Gens, A. and Vietor, T. 2010. Predictive modelling of an excavation test in indurated clay. In Clays in Natural & Engineered Barriers for Radioactive Waste Confinement, Nantes.
- Garitte B., Vaunat, J., Gens, A. and Armand, G. 3D Interpretation of an in situ heating test in the Callovo-Oxfordian mudstone. In Clays in Natural & Engineered Barriers for Radioactive Waste Confinement, Nantes.

Paper in preparation

- Analysis of the Hydro-Mechanical response of anisotropic argillaceous rocks in in-situ heating tests. by CIMNE

6.10 WP6 - Significance of TDZ in Safety Case and Input for Design

6.10.1 Objectives of WP 6

This work package aims to assess the significance of the TDZ in the safety case for disposal in clay host rock, and to provide direct feedback to repository design teams especially the thermal limits that the clays could sustain.

6.10.2 Participants of WP 6

3 Participants : SCK•CEN, NAGRA, NRG

6.10.3 Key results/achievement/deliverables

During the first period of project, a document entitled " Significance and Current Handling of the Damaged Zone in Performance Assessment" (D04/WP6- Significance and handling of DZ) was produced by PA team. The purpose of this document is to ensure that specialists in geomechanics and geochemistry active in the Work Packages 2-5 are provided early on within the project with a reasonable background on the stakes associated with the DZ in the workings of a complete disposal system. In particular, this document aims at identifying:

- how the DZ has been handled in previous performance assessments (PA);
- features, events and processes considered for scenario development purposes in PA that are potentially linked to the DZ and its evolution;
- and safety functions of the host rock and the engineered barrier system that might be affected in any way by the DZ.

On the basis of this document and all along the TIMODAZ project, phenomenology specialists are encouraged to critically review how processes linked with the DZ are translated into models or assumptions within the assessments of repository performance and safety.

The TIMODAZ results that are significant to the long-term safety of the repository have been identified and integrated within the safety case. The significance of the TDZ in the safety case for disposal in clay host rock has been assessed.

The final integration report in WP6 (D14) has been compiled by SCK•CEN, NAGRA and NRG and can be downloaded from D14 /WP6- integration of Timodaz results within Safety case and recommendation.

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 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.

The integration of the Timodaz results indicated that 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. Considering anisotropic properties of the host formations has improved the simulation results of numerical models. There is no evidence throughout the TIMODAZ experimental programme of T-induced creation of new fractures or a significant permeability increase. Instead, the experiments suggest that thermal-induced plasticity, swelling and creep are likely to be beneficial to the sealing of fractures and recovery of the permeability of the DZ. Overall, all the PA assumptions are still valid, and so far there are no indications that the thermal loading that would jeopardize the barrier capacity of host clays.

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.

The integration of the Timodaz results has been presented to end-users at 3rd end-user workshop.

6.10.4 Publications

See final dissemination plan.

6.11 WP7 - Training and dissemination

6.11.1 Objectives of WP7

This work-package brings together all activities concerning training including knowledge management and transfer. Knowledge management and the exploitation and the dissemination of results are key elements of TIMODAZ.

6.11.2 Participants of WP7

9 Participants : EURIDICE, NAGRA, SCK•CEN, CIMNE, EPFL, ULG, UJF, ENPC, ITC

6.11.3 Key results/achievement/deliverables

The activities during the whole duration of the project include:

- Organisation of two training courses
- Organisation of three end-users oriented workshops.
- And an international conference/workshop.
- Development of the TIMODAZ web site including a knowledge management tool
- More than 100 papers in the international journals and proceedings of the conference
- 1 folder

6.12 General conclusions

Timodaz has investigated the Thermo-Hydro-Mechanical and Chemical (THMC) processes occurring around a repository. It focused on the study of the combined effect of the EDZ and the thermal impact on the repository host rock.

Within Timodaz project, laboratory and in situ experiments at different scales have been conducted to study the temperature effect on the EDZ evolution. A great variety of experimental techniques not so commonly used in geomechanics were developed and applied within Timodaz to reach the objectives of the project.

Another important area of Timodaz concerns the numerical modelling development for the simulation of the THMC process around a repository at time and repository scale.

TIMODAZ has made significant contributions to the understanding the EDZ process and provided insights on the temperature effect on the DZ evolution. The similar results obtained by laboratory experiments and in situ experimentes increase the confidence for up-scaling and transfer of the knowledge from laboratory experiments, in situ tests to real repository scale.

The close collaboration between experimenters, modellers and PA team and the close link with the End-users have played an important role for the success of the Project, which allow the phenomenology specialists to target the research within the context of assessments of repository performance and safety and the priority of the end-users

6.13 Social impact

Public and political perception with respect to the nuclear waste issue will play a major role in determining the future of nuclear energy. The results of the TIMODAZ project will be situated in the context of the long-term performance of a repository. All of the experimental works to be performed in TIMODAZ will contribute to a better understanding of the processes occurring within the clay around a disposal system for heat-emitting waste during the thermal transient phase. As this transient should span over several centuries, the development and testing of sound, phenomenology-based models is an essential step towards meeting the Safety Case requirement of adequate understanding of the long-term evolution.

The knowledge gained within the TIMODAZ project allowed to assess the significance of the TDZ (Thermal Damaged Zone) in the safety case for disposal in clay host rock and provided direct feedback to repository design teams. Moreover, to ensure an appropriate and continuous link between the end-user needs and the priorities of the TIMODAZ project, the following end-user group has been constituted: ONDRAF/NIRAS (BE), NAGRA (CH), ANDRA (FR), RAWRA (CZ), ARAO (SI) and RATA (LT). This group was active throughout the duration of the project.

6.14 Project logo

6.15 Project web site :

http://www.timodaz.eu/

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Part II : Dissemination and use

7 Appendix 1 : "Final plan for using and disseminating the knowledge"