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Deliverable D7.12: Final report on influence of temperature on clays

Work Package 7, HITEC

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Executive Summary

Most Safety Cases for spent nuclear disposal facility limit maximum disposal container surface temperatures to 100°C to protect undesirable evolution. Higher temperature limits could have significant advantages such as allow disposal of higher enrichment/burn-up spent fuels and shorter interim storage/cooling requirements. EURAD HITEC WP aimed to improve Thermo-Hydro-Mechanical (THM) description of clay-based materials at elevated temperatures. The host rock clays were studied under saturated conditions under 120°C, while buffer bentonites were studied both in saturated and unsaturated conditions under 150°C.

In clay host rock, the overpressure generated by the thermal expansion of pore water and the solid rock skeleton may have deleterious consequences. In far field, this could induce rock damage and reactivate fractures/faults. In near field, this could induce fracture opening or propagation in this fractured zone, altering the permeability.

Our major observations for near field were following. Higher calcite content decreases self-sealing. Sample orientation shows no clear effect. Self-sealing is faster for tighter cracks. No significant temperature effect.

For far field, short-term and long-term (creep) compression tests were performed. The initial heating before the short-term compression tests on the COx induced transitory pore water overpressure (due to thermal expansion) and then microcracks parallel to the bedding planes. Temperature has globally a negative impact on the peak strength of the COx claystone until 100 °C. The decrease in the peak strength is the most significant for the parallel to bedding samples under uniaxial test conditions. These microcracks were also closed when the axial stress was increased during the compression tests performed perpendicular to bedding. According to the experimental results, temperature has a likely, but small under confining pressure, negative impact on the short-term resistance to failure of the COx claystone.

For bentonite buffer, proving that higher temperatures than presently accepted are suitable is very relevant even for current concepts. It increases safety margin and gives greater credibility to the design (e.g., if it is proven to work for 130°C then for 100°C it is likely to be safe). Also, this type of optimisation could be used to increase thermal limits on the bentonite buffer, reducing the footprint of the facility. So potentially significant cost savings and improved environmental sustainability.

No new processes were identified for bentonite, but swelling, swelling stress formation and water conductivity were studied in detail over 100° degrees C temperatures. Relationships delineated within Task 3.2 include: (i) the observation of swelling pressure and permeability as a function of temperature for various dry densities, swelling strains, chemical states and conditions and (ii) water retention curves, as function of temperature. For the materials and conditions tested, an influence of elevated temperature on water retention capacity has been observed. Multiple test programmes, in both Ca- and Na-bentonite have also found evidence that, whilst changes to hydraulic permeability are not very significant, swelling pressure can be substantially impacted by elevated temperatures under certain conditions. Further work to investigate and consider the mechanisms and consequences of this behaviour for repository design are recommended as a result.

The experiments and modelling at higher temperatures has required much development work, which was carried out successfully. Key results are new experimental observations and models for both materials studied in HITEC: clay host rock and buffer bentonite.

Keywords

Bentonite buffer, clay host rock, modelling, mechanical testing, THM modelling

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Glossary

Organizations :

Andra	National Agency for Radioactive Waste Management (*Agence Nationale pour la Gestion des Déchets Radioactifs*) (France)
BGE	Federal Company for Radioactive Waste Disposal mbH (*Bundesgesellschaft für Endlagerung*) (Germany)
CEA	French Alternative Energies and Atomic Energy Commission (*Commissariat à l'Énergie Atomique et aux Énergies Alternatives*) (France)
CIEMAT	Centre for Energy, Environment and Technology (*Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas*) (Spain)
CNRS	Centre national de la recherche scientifique (France)
CNRS-U Lorraine	GeoRessources, depending on the University of Lorraine and CNRS (France)
CNRS-U Grenoble	Institute of Earth Sciences (Institut des sciences de la Terre – ISTerre), depending on the University of Grenoble and CNRS (France)
CTU	Czech Technical University (Czech Republic)
CU	Charles University (Czech Republic)
EDF	Electricité de France (France)
LEI	Lithuanian Energy Institute (Lithuania)
Nagra	National Cooperative for the Disposal of Radioactive Waste (*Nationale Genossenschaft für die Lagerung radioaktiver Abfälle)* (Switzerland)
ONDRAF/NIRAS	Belgian Agency for Radioactive Waste and Enriched Fissile Materials (*Organisme national des déchets radioactifs et des matières fissiles enrichies / Nationale instelling voor radioactief afval en verrijkte Splijtstoffen*) (Belgium)
SCK CEN	Belgian Nuclear Research Centre (*Studiecentrum voor Kernenergie / Centre d'Étude de l'énergie Nucléaire*) (Belgium)
SKB	Swedish Nuclear Fuel and Waste Management Company (*Svensk Kärnbränslehantering*) (Sweden)
SÚRAO	Radioactive Waste Repositories Authority (*Správa Úložišť Radioaktivních Odpadů*) (Czech Republic)
UKRI-BGS	UK Research and Innovation - British Geological Survey (United Kingdom)
ULiège	University of Liège (Belgium)
UPC	Technical University of Catalonia (*Universitat Politècnica de Catalunya*) (Spain)
VTT	VTT Technical Research Centre of Finland Ltd (*Teknologian tutkimuskeskus VTT Oy*) (Finland)

Other acronyms:

BCV	Bentonite
CMHM	Andra research facility in northeastern France (*Centre de Meuse/Haute-Marne*)
COx	Callovo-Oxfordian claystone
EDZ	Excavation damaged zone
HHGW	High heat generating waste
OPA	Opalinus Clay
THM	Thermo-Hydro-Mechanical

URL	Underground research laboratory
WP	Work Package

1. Introduction and Task 1

1.1 Introduction

The WP7 “Influence of Temperature on Clay-based Material Behaviour” of the EJP EURAD Project aimed to develop and document improved thermo-hydro-mechanical (THM) understanding of clay-based materials (host rocks and buffers) exposed at high temperatures or having experienced high temperature transients for extended durations. The WP’s raison d’être was to evaluate whether elevated temperature limits (up to 150°C for the clay buffer and ~90°C for the host rock) are feasible for a variety of geological disposal concepts for high heat generating wastes (HHGW). For the disposal of HHGW it is important to understand the consequences of the heat produced on the properties and long-term performance of the natural and engineered clay barriers. Most safety cases for disposal concepts involving clay, currently consider a temperature limit of 100°C. Being able to tolerate higher temperature, whilst still ensuring an appropriate performance, would have significant advantages (e.g. shorter above-ground cooling times, more efficient packaging, fewer disposal containers, fewer transport operations, smaller facility footprints, etc.). Consequently, HITEC is a step toward optimization of the architecture of the deep geological disposal. HITEC looked at bentonite buffers and determined the temperature influence on buffer physical properties, swelling pressure, hydraulic conductivity, water adsorption, mineralogy and geochemistry trying to establish if the buffer safety functions are unacceptably impaired. The WP also studied the possible extent of elevated temperature damage in the near and far field of clay host rock formations (e.g. from over-pressurisation) and indicated the likely consequences of any such damage.

Figure 1 sketches the structure of HITEC (Task level), and this report structured in parallel way. In the introduction chapter the coordination, State of the art reporting, and training courses are described. The scientific content is included in chapters 2 and 3 for clay host rock and clay buffers, respectively. Finally impact of HITEC and especially Safety case guidance are prescribed in chapter 4. The more detailed subtask structure of HITEC is followed inside of all chapters. This report is only focused on objectives, short description of work done and major conclusions. For more detailed information, the deliverables of HITEC are sketched in Figure 2 and Table 1.

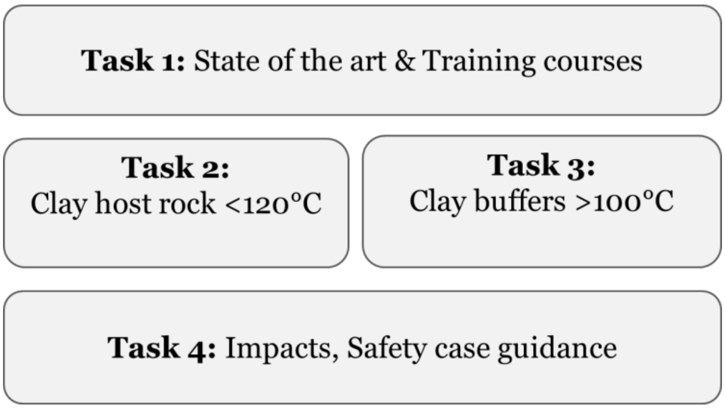

Figure 1 – Structure of HITEC.

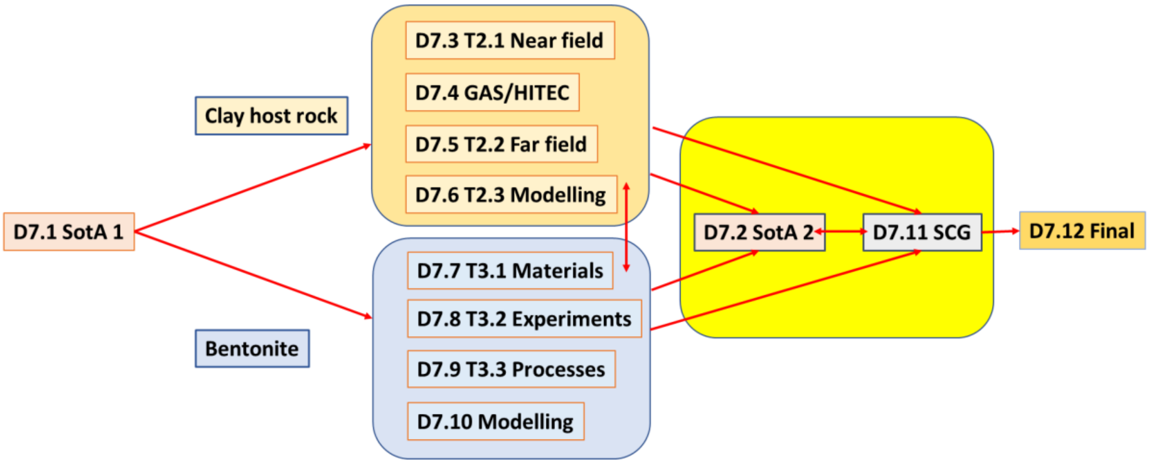

Figure 2 – All HITEC deliverables, on which this report is based, and how they are related to each other.

Deliverable	Title	
D7.1	State-of-the-art on THM behaviour	SotA
D7.2	Updated State-of-the-art on THM behaviour	SotA
D7.3	Final report on thermal effects on near field	Clay host rock
D7.4	Specific GAS/HITEC self-sealing processes	Clay host rock
D7.5	Final report on effect on far field properties	Clay host rock
D7.6	Final modelling report on near field	Clay host rock
D7.7	Material characterisation – Task 3.1	Bentonite
D7.8	Report on test at high temperature – Task 3.2	Bentonite
D7.9	Experimental work T3.3	Bentonite
D7.10	Results of modelling carried in T3.3	Bentonite
D7.11	Guidance for safety case development and repository optimization	Guidance
D7.12	Final report on influence of temperature on clays	Final report

Table 1 – All deliverables of HITEC.

1.2 Task 1: Coordination and training

The coordination and training task consisted of three subtasks: coordination, state of the art reporting and training.

1.2.1 Coordination Task 1.1

The coordination subtask was led by VTT, and the task was responsible on overall coordination of HITEC, reporting and WP Meetings. The first meeting was a kick-off meeting of HITEC in Paris, in June 2019, and the last one Final workshop in Bucharest, April 2024, together with the GAS WP. In addition of these, eight progress meetings were arranged.

1.2.2 State of the art reporting – SotA, Task 1.2

The first version of the SotA was published as D7.1 early 2020 (Villar et al., 2020). It was written mainly by Waste management organisations (WMO). An updated version of the State-of-the-Art report is being prepared for publication (Villar et al., 2024). It will be a summary of the initial version and include a synthesis of the major achievements during the project. The final SotA is also published as D7.2 (Villar et al., 2024).

This SotA-report summarises results obtained in Tasks 2 (clay host rock) and 3 (bentonite buffer) of the HITEC, along with others from the literature, concerning the impact of high temperature on the behaviour of clay materials. Bentonites under assessment included Wyoming-type (MX-80, Barakade), BCV and FEBEX, and the clay formations studied were Boom Clay, Opalinus Clay and Callovo-Oxfordian claystone.

The material submitted to high temperatures over long periods experiences desiccation and other changes that may affect its long-term performance if they were irreversible. This concern has been tackled in HITEC by subjecting bentonite to high temperatures under different conditions and time periods and determining their characteristics and properties afterwards. The most representative condition would be that experienced by the material in field tests, such as the ABM5, which are also in operation for several years, and in laboratory thermo-hydraulic tests in cells that reproduce the in-situ conditions in a controlled way. An additional approach is the drying of powder material in the oven, which simulates the transient situation of the buffer closest to the canisters. The clay crystallo-chemistry was preserved in all cases and changes, such as the Mg enrichment or slight increase of trioctahedral character of smectite, could not be specifically linked to the high temperature, because they had also been observed under lower temperatures. If evaporation during drying was allowed, the changes were more important, generally consisting in decreases in cation exchange capacity, specific surface area, water adsorption capacity and sorption coefficients. However, heating under wet conditions had the opposite effect on these properties. It is presumed that these changes were caused not by the temperature itself, but by the loss of the water induced by the elevated temperature. Additionally, some of these changes, such as the decrease in water adsorption capacity, are reversible when the material is rehydrated. The hydro-mechanical properties of preheated material were only affected in samples heated under dry conditions and compacted at high dry density, in which a slight increase in hydraulic conductivity was observed.

The field and laboratory tests imply hydration under thermal gradient, and consequently water movement and associated geochemical processes. As it had been observed under lower temperatures or thermal gradients, dissolution and precipitation of species occurred in those tests, along with modification of the exchangeable cation complex of the smectite. These processes were conditioned by the kind of bentonite and hydration water. Some of the modifications observed, e.g. corrosion, were less pronounced compared to other tests conducted at lower temperature but with higher water contents.

The hydro-mechanical properties of the compacted bentonite have been determined in HITEC across a range of temperatures (predominantly 80-200°C). The determination of properties at high temperatures is technologically challenging and the procedures followed, despite the significant advances in methodology and equipment made during the project, may greatly impact the results. Hydration and swelling pressure development were quicker as the temperature was higher. Once saturated, higher temperatures resulted in lower swelling pressures for all bentonites (but not for calcium-exchanged purified smectite). However, under some particular conditions (heating under isochoric conditions a material previously saturated at room temperature) progressive and permanent decrease of the swelling pressure with respect to the one measured at the end of saturation was observed (thermally-induced creep). The underlying mechanisms that could explain this behaviour are unknown. This decrease in swelling pressure was not accompanied by impacts on hydraulic conductivity, which was not detrimentally affected by thermal loading up to temperatures of 200°C. The water retention capacity decreases with temperature, more significantly for the predominantly sodic materials. The results consistently indicate that the effect of temperature is small below 80°C and, for higher temperatures, is more significant for the higher dry densities. In any case, even at the highest temperatures, the bentonite had the ability to fill voids and was able to develop large swelling pressures at high densities. Given the impact that experimental boundary conditions may have on the results obtained, assessment of measurements in field tests would be very helpful to confirm the long-term evolution of swelling.

It is considered that THM formulations for expansive materials developed and validated for temperatures below 100°C can be extended to temperatures above that value by including the thermal dependence of some parameters, such as the water retention curve, permeability, thermal conductivity, surface tension, volumetric behaviour of the microstructure and normal compression behaviour of the macrostructure. The modification during HITEC of previous models also included the incorporation of the hydro-mechanical coupling between the micro- and macropore levels and the definition of retention curves for each structural domain. To further improve the models, inclusion of the dependence of the water retention curves on the evolution of the micro and macropore volume fractions may be necessary. A lack of experimental data to enable the quantification of the microstructure of compacted bentonites, which influences the calibration of microstructural parameters, has been identified.

As it happens for the buffer, working at high temperature with claystone is challenging, and the impact of the testing protocols (thermal loading rates, stress conditions) on the results obtained is also a concern. For example, modelling of the triaxial tests showed that, if fast heating rates (not representative of the actual case) are applied under undrained conditions, overpressures may build up and the samples may be damaged.

Important hydro-mechanical couplings between peak pore water pressure, temperature, permeability and confining stress were identified. The results of the laboratory experiments confirmed that the claystone keeps its good mechanical and retention properties, even when heated at up to 100°C. Nonetheless, considering the heat output of the waste and the thermally induced pore water pressures, a repository should be located at a depth below which thermally induced pore water pressures could remain lower than the in-situ stress.

Although many parameters can influence the efficiency of the self-sealing process (calcite and clay content, sample orientation with respect to bedding, temperature), confidence was gained in the positive impact of the self-sealing process on the restoration of the initial sealing properties of the clay host rock, especially because the duration of the laboratory experiments was much shorter than the repository time scale. Temperature may have a slight delaying effect on the self-sealing process though.

The modelling activities undertaken during HITEC intended to compare the output of the different codes used by the participants and the behaviour of the three clay host rocks. One of the benchmarks consisted in the modelling of a near-field generic case, which showed the pore pressure build-up resulting from the heating applied to the clay host rock, and as expected, a relatively lower overpressure in the softer Boom Clay than in the Opalinus clay and the COx claystone. All the models predicted that the high plastic strains (associated to the EDZ development) are always localised in the very near field. The consistency among the simulation results of different groups for the far-field improves confidence in the modelling approach used to dimension repositories.

Very consistent results can be obtained with different codes using a poro-elastic approach when the parameters and boundary conditions are correctly set. For example, the evolutions of temperature and pore pressure in field tests were well modelled in the far field with an anisotropic poro-elastic approach, but more advanced models are needed to account for the processes occurring around the tunnels (e.g. modification of hydraulic and mechanical properties within the EDZ, creep). Accurate knowledge of the stiffness and permeability of both the sound and the damaged clay rock are necessary for a good reproduction of field results.

1.2.3 Two training schools, Task 1.3

The first GAS/HITEC Joint training course (Collin & Charlier, 2020) was a Doctoral School entitled "Multiphysical Couplings in Geomechanics, a focus on thermal effect and gas transfer impact on the behaviour of geomaterials". The school was organized from 22 to 24 January 2020 at Liège University, within the framework of EURAD.

This doctoral school was related to two of the WPs of the EURAD Joint Programme, namely the GAS and HITEC WPs. In both WPs, geomechanics plays a significant role in the understanding of the relevant thermo-hydro-mechanical couplings taking place around the disposal area. The objectives of the school were therefore to present the students with the state-of-the-art on basic concepts related to the thermo-hydro-mechanical (multi-physical) couplings, the physical impacts of thermal loading and a mechanistic understanding of gas migration. The deliverable D6.3 (Collin & Charlier, 2020) is related to the 1st GAS/HITEC training course.

The second GAS/HITEC Joint training course (D6.4, Collin, 2024) was organised jointly with the ALERT Geomaterials network. The school was organized from 28th August to 1st September 2023 at Liège University, within the framework of EURAD: GAS and HITEC WPs. Geomechanics plays a significant role in the understanding of the multiphysics and multiscale processes taking place in a geological disposal facility for radioactive waste. The objective of the school was to introduce state-of-the-art understanding, concepts and methods related to thermo-hydromechanical coupled processes, the physical impacts of thermal loading and the mechanistic understanding of gas migration in geomaterials. Results produced in the past four years from the EURAD projects, and the scientific community of ALERT have been integrated to the school. A visit to the HADES Underground Research Laboratory was organised on the last day of the school. A half day has been dedicated to presentations by early-career researchers) and a visit of the Geotechnical Laboratory from ULiège.

2. Task 2: Clay host rock

Task T2 Clay host rock consisted of three subtasks: subtasks 2.1 (D7.3) and 2.2 (D7.5) experimental work for near and far field respectively, and subtask 2.3 modelling (D7.6). In addition, collaboration about self-sealing was carried out with the GAS WP (D7.4).

Within the HITEC WP, Task 2 focused on the behaviour of the clay host rocks at temperatures of up to 120°C to help to optimise the repository design. Indeed, the heat generated by waste must not affect the favourable properties of the host rock, especially its transport properties, for containment. The overpressure generated by the difference between thermal expansion coefficient of pore water and the solid rock skeleton may have deleterious consequences. In the near field (i.e., in the vicinity of the cell) characterised by a fractured zone, this could induce fracture opening or propagation in this fractured zone, altering the permeability. In far field, this could induce rock damage and reactivate fractures/faults.

2.1 Subtask 2.1 Lab experiments for near field with EDZ

Main objective of Subtask 2.1:

Provide answers (through lab experiments) about the effects of increased temperature on fracturing and self-sealing processes of clay host rocks in the excavated-damaged zone.

Subtask 2.1 used **lab experiments** to assess a possible extension of the excavation induced fracture network, investigating the role of the fracture network on the containment properties of the host rock. Three organisations were included in this subtask: [CNRS (**ULorraine**)] (subtask leader), [CNRS (**UGrenoble**)] and [**UKRI- BGS**], which studied COx (self-sealing tests in triaxial cell), OPA (self-sealing tests in oedometric cell) and Boom Clay (self-sealing tests in shear rig), respectively. The objectives, methods and results are fully reported in D7.3 (Grgic et al., 2024a).

The main observations were:

- Higher calcite content decreases self-sealing
- Sample orientation shows no clear effect
- Self-sealing is faster for tighter cracks

- No significant temperature effect, Callovo-Oxfordian claystone and Opalinus Clay, which may have minimal self-sealing potential at 90 °C when hydration is associated with significant shear

Laboratory experiments in subtask 2.1 were performed to provide answers about the impact of heating on the self-sealing processes in the near-field. Different testing cells (triaxial, oedometric and shear ring) and monitoring tools (X-ray and neutron tomography) have been used by the different partners to analyse, at different test stages and temperatures, the evolution of crack volume and permeability of fractured samples due to water percolation. The materials used in this study were: Callovo Oxfordian claystone (COx), Opalinus clay (OPA) and Boom clay.

CNRS (ULorraine) analysed the self-sealing process in the Callovo-Oxfordian claystone by performing self-sealing tests on initially (artificially) fractured samples under different temperatures with water injection. Cylindrical samples oriented in parallel and perpendicularly to the bedding plane with an artificial initial fracture were used in a triaxial compression cell transparent to X-rays. Water permeability was measured and the evolution of cracks volume was analysed from X-ray tomography 3D images to characterize the self-sealing process. All tests performed at 20 °C with water injection showed a rapid drop in permeability at the beginning followed by a progressive decrease and a stabilization after one month. The permeability of fractured samples decreases significantly after self-sealing but is still higher (by 2 orders of magnitude) than the permeability of healthy claystone. Otherwise, the less calcite the sample contains (i.e., the more clayey it is), the faster the crack self-seals. The smaller the opening of the initial crack is, the faster the water permeability decreases and the crack closes. No significant influence of the sample orientation on the self-sealing kinetic was identified at this stage. Finally, temperature doesn't seem to have a significant impact on the self-sealing process (permeability decrease and crack volume reduction).

CNRS (UGrenoble) carried out a comparative study of self-sealing at different temperatures (between 25 and 90°C) to investigate the re-sealing phenomenon in Callovo-Oxfordian clay rock. The samples, which had an initial opening, were monitored throughout the test under in operando conditions, using tomography with simultaneous combined x-ray and neutron imaging. X-ray tomography was used to quantify variations in mass density and, combined with digital image correlation (DIC), to quantify the kinematic field (in particular the volume strain field). Neutron tomography is used to quantify the presence of water in the material, as neutron absorption is very sensitive to the hydrogen in water. The samples were first heated (outside the tomography line) and then, once installed in the tomograph, synthetic water (with in situ salinity) was injected into the initial crack. Scans were taken every fifteen minutes for several hours. The comparative analysis revealed similarities and differences in the sealing process, depending on the temperature. Reclosure of the initial crack is fairly rapid, taking a few hours. However, if we reason in terms of mass density, the density of the material filling the initial crack does not reach the density of the sound material during the few hours of testing. The self-sealing process is a multi-stage process, with a rapid filling phase and a slower process, which could not be studied here. One difference attributed to temperature concerns the self-sealing mechanisms. At room temperature, the filling of the initial crack is induced by the formation of a dense network of secondary micro-cracks in the vicinity of the initial crack, forming a highly damaged material that fills the empty space. There is also swelling of the material in the remainder of the sample. At a temperature of 90°C, the self-sealing process is essentially attributed to diffuse swelling of the material in the sample, the amplitude of which is greater than at room temperature. Secondary cracking, as described at room temperature, is not observed here, or only sporadically. The neutron tomography images show that, in both cases, the initial crack opening is replaced by a material with a slightly higher water content than the intact material and that the water propagates through the sample, accompanying the swelling process.

UKRI-BGS performed self-sealing experiments in Opalinus Clay (OPA) and Callovo-Oxfordian claystone (COx). Starting with intact cylindrical sample, a shear-fracture was created at the mid-plane in a direct shear apparatus. The addition of an injection bore then allowed synthetic pore fluid to be delivered directly to the fracture plane to monitor flow. The decrease in initial flow to a steady value determined the self-sealing potential (SSP) from hydration, while comparing flow on the static fracture with changes in flow as a result of shear determined the self-sealing potential from shear. Two batches of experiments were conducted: the first had fractures formed at ambient temperatures, which were then tested for flow at elevated temperatures between 20 and 90°C. The second batch had the fracture and flow parts of the experiment both conducted at temperature. Temperature was seen to have a considerable effect on the shear properties of OPA and COx, with peak strength and shear modulus increasing with temperature. Self-sealing potential as a result of hydration and shear was seen to reduce to a negligible amount at 90 °C in both OPA and COx. In COx, two orders of magnitude reduction in SSP as a result of hydration was seen. The study indicates that the favourable self-sealing properties of OPA and COx may reduce with temperature and become almost negligible at 90 °C. Further analysis are needed to understand the processes inducing this behaviour

2.2 Subtask 2.2 Lab experiments for far field

Main objective of Subtask 2.2:

To provide answers (through lab experiments) about the effects of increased temperature on the short and long-term mechanical behaviours (deformations, elastic properties, failure strength) and on evolution of damage and intrinsic permeability due to porewater overpressures.

Subtask 2.2 used **lab experiments** on materials at elevated temperatures. It focused on the thermal pressurisation and the risk of damage when the effective stress increases up to the overburden weight. This a far field topic was carried out by [**CEA**], [CNRS (**ULorraine**)] [**UKRI-BGS**] and [**RWM**]. CEA studied Opalinus and Boom Clay by triaxial creep tests, ULorrraine studied COx by short-term triaxial compression tests and triaxial creep tests, and BGS studied Opalinus, Boom Clay and COx by measuring effect of porewater overpressure on THM behaviour and permeability in load cell. The objectives, methods and results are fully reported in D7.5 (Grgic et al., 2024b).

Main observations were:

- Temperature has globally a negative impact on the peak strength of the COx claystone until 100 °C.
- The decrease in the peak strength is the most significant for the parallel to bedding samples under uniaxial test conditions.
- These microcracks were also closed when the axial stress was increased during the compression tests performed perpendicular to bedding.
- According to the experimental results, temperature has a likely, but small under confining pressure, negative impact on the short-term resistance to failure of the COx claystone.

Laboratory experiments in subtask 2.2 were performed to provide answers about the impact of temperature on the short- and long-term (i.e., creep) mechanical properties of clay host rocks in the far-field. In addition, the magnitude and impact of thermally induced porewater pressures on the evolution of damage and intrinsic permeability in candidate clay host rocks was examined experimentally. Different testing cells (triaxial, oedometric) have been used by the different partners to achieve these goals. The materials used in this study were: Callovo Oxfordian claystone (COx), Opalinus clay (OPA) and Boom clay.

CNRS (ULorraine) analysed the effect of temperature on the mechanical behaviour of the Callovo-Oxfordian claystone in the context of deep geological disposal of radioactive waste in France. First, compression tests in a triaxial cell were performed under pseudo-drained condition with strains measurements, at different temperatures (20, 40, 60, 80, 100 and 150 °C), confining pressures (0, 4 and 12 MPa) and samples orientations (parallel and perpendicular to the bedding plane) to characterize the short-term mechanical behaviour. Second, multi-step creep tests in a triaxial cell with axial and lateral strains measurements were carried out at different temperatures (20, 40, 60, and 80 °C), for different confining pressures (2 and 12 MPa) and orientations (loading direction parallel and perpendicular to the bedding plane) to characterize the long-term mechanical behaviour. From the short-term compression tests, the analysis of elastic coefficients indicates that in all cases an anisotropic damage develops during the deviatoric loading due to the opening of axial microcracks. In addition, the peak deformation and strength increase when confining pressures increases. The initial heating stage generates a transitory pore water overpressure due to thermal expansion, which creates microcracks probably parallel to the bedding plane. Despite the scattering of some results, an overall decrease of the peak strength with increasing temperature (until 100 °C) is observed because of to the thermo-hydro-mechanical damage induced by the initial heating. For the parallel samples under uniaxial conditions, this decrease is the most important and volumetric dilatancy develops during the loading for the highest temperatures. For all other conditions, the decrease is more moderate and there is no dilatancy because confining pressure reduces the creation of initial thermo-induced microcracks which are also closed when the axial stress was increased during the compression tests when the orientation is perpendicular. There is no noticeable impact of temperature up to 100 °C on the evolutions of the elastic coefficients. The peak strength increases at the highest temperature (150 °C) in all cases due to the water vaporisation and then strong samples desaturation, which induces the development of a very significant capillary suction. So far, only multi-step creep tests at T = 20 °C and Pc = 2 and 12 MPa, and at T = 80 °C and Pc = 12 MPa, for both parallel and perpendicular samples, were performed on the COx claystone. These first results showed that creep deformations are larger at higher temperature (80 °C) and that long-term strength seems to decrease with temperature. This conclusion has obviously to be confirmed when all the creep tests at different temperatures will be finished.

CEA realised a series of triaxial creep tests with two different claystones, Boom Clay and Opalinus Clay. First confined under isotropic stress, the samples were saturated with the adequate synthetic water, specific to each kind of claystone, injected at a constant pressure. Then the samples were heated up to a precise level of temperature which was maintained constant up to the end of the experiment. Then several successive deviatoric stress levels were applied to the sample to investigate their time dependent behaviour. There were a series of multi-steps triaxial creep tests. Each experiment is performed under a constant temperature. Two testing benches, each equipped with two companion triaxial HOEK-type cells, were operated. Each bench ran with a specific temperature, maintained constant during all the creep sequences. Note that during the heating phase and during the creep sequences the drainage between the sample and the pore pressure tank was allowed, which maintained a constant pressure. As such, the creep experiments were conducted under drained conditions. With Boom Clay, the time-dependent behaviours have been investigated under three levels of temperature: 40°C, 60°C and 80°C. At 40°C three sequences of creep have been made with a maximal deviatoric stress equal to 3.51 MPa. Four creep sequences were made at 60°C, the maximal deviatoric stress was equal to 5.97 MPa. At 80°C a maximal deviatoric stress of 2.60 MPa was reached at the second creep step. Both the magnitude and the evolution kinetics of the creep strain were greater when the temperature was higher. With Opalinus Clay, two levels of temperature have been investigated: 40°C and 80°C. For each value of temperature, five creep sequences have been realised, with the maximal values of the deviatoric stresses equal to 9.17 and 10.0 MPa, for 40 °C and 80 °C respectively. The comparison between the two series of tests shows clearly that the magnitude of the strain is increased when the temperature was higher. Moreover, the kinetics is accelerated with higher temperature, and the strain stabilisation occurred later. The results of that experimental campaign show clearly that several tests are necessary to correctly investigate the time-dependent behaviour of each claystone. The natural variability between the two samples over-cored inside the same initial core of claystone seems to have a great influence on the magnitude of the strains. The kinetics of the evolution of the strains seems to be less sensitive to this variability. Some samples failed too early, preventing the experiment to be continued.

BGS undertook a series of oedometric (K0) experiments on candidate host rocks measuring the spatial and temporal development of porewater pressure caused by its thermal expansion and its subsequent impact on the evolution of intrinsic permeability. Experiments were performed across a range of temperatures from 20 to 90°C. Results demonstrate that in all cases the permeability was observed to decrease on heating, with the rate of change linked to the initial permeability of the sample. In Opalinus

Clay (OPA), heating to around 70°C resulted in the development of local porewater pressures exceeding the axial stress, with peak pressure increasing with temperature. Porewater pressures exhibited local anisotropy and possible heterogeneity effects on the length-scale of the experiments. The permeability of the Callovo-Oxfordian (COx) was shown to be considerably lower than that of OPA, leading to higher peak porewater pressures and possible evidence of thermally induced mechanical failure. However, in all experiments, no evidence for the degradation of hydraulic properties was observed once temperatures had dissipated. Hydraulic anisotropy was measured for flow parallel and perpendicular to bedding and the impact of possible sample damage was explored. This study identified important hydromechanical couplings between peak porewater pressure, temperature, permeability and confining stress. Using these relationships, and a knowledge of the heat output of the waste, it is possible to calculate a repository depth below which thermally induced porewater pressures could be managed and always remain lower than the in-situ stress. While K0 experiments allow the measurement of formation overpressures, they impose a slightly artificial boundary condition and, when testing indurated materials such as OPA and COx, can be difficult to seal. However, although achieving an adequate seal is a complex task, the hydromechanical couplings identified by this study provide important insight into the integrity of the host rock and ultimately, safety assessment.

2.3 Subtask 2.3 Modelling

Main objective of Subtask 2.3:

To improve understanding of the THM (Thermo-Hydro-Mechanical) behaviour of clay host rock at elevated temperature.

Subtask 2.3 focused on the development of **THM models** which are able to consider processes studied in subtasks 2.1 and 2.2.

Investigating the influence of thermal loading on the behaviour of clay-based materials, a series of benchmarking exercises were proposed to eight European modelling teams, based on the concepts of radioactive waste disposals developed by Andra, Euridice and Nagra. The benchmark was divided in three consecutive steps. The teams first worked on 2D generic models in order to study the near-field and far-field effects of heating on the behaviour of clay rocks. Three clay formations considered to host potential radioactive waste repositories were studied: the Callovo-Oxfordian (COx) claystone, the Boom clay and the Opalinus clay. For the near-field models, three subcases were proposed with an increasing level of complexity, starting from elastic isotropic conditions and finishing with anisotropic stress conditions and the development of elasto-plastic/damage models. Some triaxial compression tests performed in the experimental part of the project were then studied. Finally, two full-scale in-situ heating experiments were modelled: the ALC1605 experiment performed in the COx claystone, and the PRACLAY Heater test experiment in the Boom clay.

Eight modelling teams participated in this exercise:

- ANDRA, BGE, CNRS-3SR, EDF, EURIDICE, LEI, ULiege, UPC

They applied these six modelling codes:

- Code_Aster, CODE_BRIGHT, COMSOL, FLAC3D, Lagamine, OpenGeoSys (OGS)

Major results and observations

- **Near-field benchmark**
    - Very consistent results in the elastic isotropic case
    - More variations on pressure prediction in the anisotropic case, likely due to:
        - Differences in the THM formulations and assumptions made in the different codes
        - Mesh dependency

  - Models able to represent the development of the EDZ
    - Some variations on extent of EDZ, but effect of heating limited to very near field. No extension of the EDZ during 10 years of heating
- **Far-field benchmark**
  - Run only on COx case
  - Near-field effects do not affect the affect the results in the far-field. Positive impact of creep
  -
  - Consistent results obtained by 6 teams with 5 different codes at mid-distance between two microtunnels
    - Builds confidence in this type of anisotropic poroelastic model that is known to provide a good prediction of the evolution of both T and PP in the far-field
    - Confirms the robustness of the modelling approach used to dimension the Cigéo deep geological disposal facility
- **Modelling of subtask 2.1/2.2 lab experiments**
  - Modelling of subtask 2.1 triaxial compression tests on heated COx samples
  - A good understanding of the experimental setup and of the boundary conditions is essential for correct interpretation of the experiments and use of their results
  - Modelling of the heating phase under undrained conditions revealed the generation of overpressures when fast heating rates were applied, inducing some damage in the samples
    - May explain the strength reduction observed in the tests conducted at low confining pressures, implying that the heating phase was not conducted under fully drained conditions.
      - Post-mortem analysis of samples heated in the ALC1604 and CRQ in-situ heating experiments in the CMHM URL show no change in mechanical properties
  - Some models were developed to take into account strength decrease with temperature
    - Impact on near-field and far-field calculations to be evaluated.
- **Modelling of in-situ experiments**
  - ALC1605 (COx) and PRACLAY Heater test (Boom Clay)
    - In both cases, the teams successfully managed to reproduce the anisotropic response of the clay host rocks to excavation and heating.
    - The evolutions of temperature and pore pressure were well modelled in the far-field with a poro-elastic approach
    - More advanced models are needed to take into account the processes occurring around the tunnels (e.g., modification of hydraulic properties within the EDZ, creep).

    - The parameters that played a significant role to reproduce accurately the measurements were the stiffness of the intact clay rock and of the damaged clay, and the permeabilities in both zones.
- All objectives, methods and results presented in D7.6 (de Lesquen et al., 2024**).**

2.4 Self-sealing

This objective of this program developed during the EURAD project was to evaluate the consequences of temperature and gas on self-sealing capacity of three clay host rocks and a bentonite material.

Several experiments were conducted by seven partners covering different kinds of situation. These laboratory experiments performed in the GAS and HITEC work packages confirm the good self-sealing capability of three clay host rocks, the Boom Clay, the Callovo-Oxfordian claystone and the Opalinus Clay. After exposure to water, the permeability of fractured clay rocks decreases rapidly (in a matter of hours or days) and becomes close to that of the intact rock even if they have been submitted to gas flow or to temperature.

The self-sealing ability of bentonite is also essential for the safe design of a deep geological repository. Under high gas pressure loading, a dilatant pathway is formed in the bentonite, which may be a preferential pathway for radionuclide leakage. The GAS experiments on BCV bentonite showed that after three months of saturation following a breakthrough event, the sealing properties of bentonite are not compromised by breakthroughs caused by high gas pressure in key parameters (hydraulic conductivity and swelling pressure). No significant changes were also observed after one year of cyclic loading with fast gas tests. The conclusion that there is no effect on the sealing properties of BCV bentonite after repeated breakthrough events is the same for samples compacted homogeneously or with an artificial joint.

The project confirmed that modelling self-sealing processes in host rock is a real challenge. Few models are available or have been developed to model self-sealing processes in the clay host rock. The work performed by ULiege integrating in the Lagamine code a new hydro-mechanical constitutive model based on several experimental observations gives interesting results. This model is based on the observation that the saturation phase generates micro-cracks around the fracture, defining a low-density and fairly compressible zone. It was able to reproduce experimental tests performed on fracture samples. Both the fracture closure during hydration and the fracture opening when the fracture material is submitted to drying are well reproduced.

Overall, these results are very promising and give confidence in the self-sealing capacity of both the bentonite barriers and of the clay rocks identified to host radioactive waste disposals. Complete description about self-sealing work, methods and results are given in D7.4 (Talandier et al., 2024).

3. Task 3: Bentonite buffer

Task T3 Bentonite buffer, consisted of three subtasks: subtasks 3.1 (D7.7) material subjected to high temperature and 3.2 (D7.8) processes and behaviour at high temperature, and subtask 3.3 experiments (D7.9) and modelling (D7.10) at high temperature.

3.1 Subtask T3.1: Material subjected to the high temperature

Main objectives of Subtask 3.1:

- Investigate material changes after high temperature treatment on the safety functions (important properties) and on its integrity (e.g. mineralogy, chemistry, mechanical parameters…)
- Determination of parameters necessary for mathematical modelling e.g., to fill up blank spots in material database for temperatures above 100°C

Material subjected **to the high temperature** was studied and changes of properties were determined. Both laboratory-treated material and samples from (in-situ) experiments were included. Ten organisations were included **[CIEMAT (UAM)]** [KIT (**BGR**)] [ChRDI (**KIPT**) **(SIIEG NASU)] [SKB]** [SURAO (**CTU**) (**CU**) (**UJV**)] [**UHelsinki**] **[VTT].** They studied these properties of bentonite:

- Mechanical properties
- Hydraulic properties and swelling
- Mineralogy
- Geochemistry

The main observations were:

- In several cases the *CEC* of the bentonite was affected by the heating.
- There are indications that dry heating of bentonite seems to affect the clay in other ways, than heating of water saturated bentonite.
- Swelling pressure seemed mainly unaffected by thermal treatment, while hydraulic conductivity sometimes increased somewhat. (dry treated material)
- The liquid limit and swell index of dry treated bentonite are lower. The decrease of both parameters is observed as a function of the heating time (probably stabilises).
- Unconfined compression test showed that a lower maximum deviator stress was seen in all materials compared to the references.
- There were examples of (i) redistribution of sulphates, (ii) formation of carbonates, (iii) dissolution of quartz and cristobalite.
- There were examples of compacted bentonite blocks that were physically disintegrated in parts of the experiments. The mechanism for this is not fully understood, and it is unclear if this could happen in a real repository as well at high temperatures.
- None of the analyses performed could detect any specific high temperature reaction.
- During the test period the experiments did not alter the bentonite in a way that it lost its important properties as a buffer material.

Several different high temperature experiments were performed with bentonite clays. Both field experiments at a hard rock laboratory and laboratory scale experiments have been performed. Some experiments by heating the clay either in an open system while allowing the clay to dry or in a closed system with water available. No general significant transformation of montmorillonite was observed in the experiments. In several cases the *CEC* of the bentonite was affected by the heating, but with no correlation to any observed mineralogical changes.

There are indications that dry heating of the bentonite had a stronger impact on the clay properties, than heating of water saturated bentonite. Swelling pressure seemed mainly unaffected by thermal treatment, while hydraulic conductivity sometimes increased somewhat. Unconfined compression test showed that a lower maximum deviator stress was seen in all materials compared to the references in the ABM5 field test.

There were examples of (i) redistribution of sulphates, (ii) formation of carbonates, (iii) dissolution of quartz and cristobalite. These are observations that are not new. There were examples of compacted bentonite blocks that were physically disintegrated in parts of the experiments. The mechanism for this is not fully understood, and it is unclear if this could happen in a real repository as well at high temperatures. Possibly it was due to the delayed heating in relation to the water saturation of the bentonite clay. The liquid limit and swell index of dry treated bentonite are lower than corresponding reference material. The decrease of both parameters is observed as a function of the heating time. None of the analyses performed could detect any specific high temperature reaction. During the test period the experiments did not alter the bentonite in a way that it lost its important properties as a buffer material.

3.2 Subtask T3.2: Investigation of processes and material behaviour at higher temperatures/transients.

Main objectives of Subtask 3.2:

- Investigate processes and material properties at high temperature
- Determination of parameters necessary for mathematical modelling (input into Subtask 3.3)

Subtask T3.2 focussed on investigation of processes and material behaviour at higher temperatures/transients.

The organisations participating were: **[Andra]** [**UKRI-BGS**] [ChRDI (**KIPT**)] **[CIEMAT] [RWM]** [**SURAO** (**CTU**) (**CU**)] [UHelsinki (**GTK**) (**JYU**)] **[VTT]**

The materials studied were:

- MX-80
- Imersys Ca bentonite
- Kunipia G
- FEBEX
- BARA-KADE
- BCV
- PBC

The phenomena and processes studied were:

- Swelling pressure and permeability
- Water retention curves
- Oedometric compressibility
- Saturation development

The major observations were in:

- Swelling pressure and permeability
- Water retention curves
- Oedometric compressibility
- Saturation development
- Material at temperatures analysed
    - Properties determined
    - Stability over time examined (it needs more characterisation)
- Initial material dataset into numerical models (it needs more work)
- Some effects start well below 100 °C
- Unexpected phenomena identified - needs more characterisation and implementation into models: e.g., , swelling pressure can be substantially impacted by elevated temperatures

- Does not prevent usage of higher temperatures in repository, but it needs more work
- Current models/designs need to be checked/updated based on results if all phenomena included (minor)

The objectives of this task were focussed around evaluating the behaviour of clay buffer materials at high temperature. The findings are expected to inform the feasibility of designing geological disposal facilities to operate at elevated temperature conditions. Despite delays resulting from the Covid-19 crisis, substantial progress has been made in the development and construction of a wide range of experimental apparatus within this task. Progress has been made in the development of imaging methodologies and preliminary observations indicate that the uptake of water is sensitive to elevated temperatures. Relationships delineated within Task 3.2 include: (i) the observation of swelling pressure and permeability as a function of temperature for various dry densities, swelling strains, chemical states and conditions and (ii) water retention curves, as function of temperature. For the materials and conditions tested, an influence of elevated temperature on water retention capacity has been observed. Multiple test programmes, in both Ca- and Na-bentonite have also found evidence that, whilst changes to hydraulic permeability are perhaps less significant, swelling pressure can be substantially impacted by elevated temperatures. Further work to consider the mechanisms and consequences of this behaviour for repository design are recommended as a result.

The extensive datasets generated by this Task 3.2 will enable the parameterisation, modification and validation of numerical simulations to more accurately represent the thermo-hydro-mechanical behaviour of bentonite at elevated temperatures.

3.3 Subtask T3.3: Experiments and modelling at high temperature

Main objective of Subtask 3.3:

- Understanding of processes at larger scale
- Development and validation of mathematical models (at concept/element level)
- Benchmark of available and developed codes to assess their suitability for high temperatures

Subtask 3.3 focused on experiment designed to simulate processes in clay buffer at various level of complexity. These experiments created basis for system behaviour understanding and database for mathematical model validation. It also focused on conceptual development of **mathematical models**. Model validation carried out by data from T3.1 and 3.2. Benchmarking the codes in cooperation with DONUT.

Experiments

- Data
  - Model development and validation
- Samples
  - Analysed within T3.1
  - Results coherent with results from lab tests

Models

- Calibration data from T3.1 and T3.2 incorporated
- Models improved to represent behaviour above 100 C. However, some effect of temperature still need to incorporated
- Models validated/benchmarked against experiments
- Joint benchmark with DONUT

The major observations were:

- Dataset - properties and behaviour of bentonite at high temperature + bentonite exposed to high temperature
- Numerical code development and validation. Important step in order to achiever proper representation of bentonite behaviour in numerical models at higher temperature. However, there is still some work to do.
- An important base step in order to be able to describe and model EBS at higher temperatures
- In some areas a decrease of performance has been detected. However, nothing major preventing high temperature concept to be fully developed.
- Some effect observed below 100 C – input into current design
- Some areas need more investigation (sparser dataset, thermal relaxation)

3.3.1 Experiments (D9)

CIEMAT and SÚRAO [CTU] performed thermo-hydraulic tests intended to simulate the conditions of the bentonite buffer in the repository. Namely two kinds of tests were performed:

- hydration tests under thermo-hydraulic gradient (TH tests), and
- hydration tests under high isothermal temperature.

The first group of tests, in which the buffer material is simultaneously submitted to thermal and hydraulic gradients in opposite directions, aimed to simulate the conditions of the whole barrier during operation, where the temperatures may be significantly different from those areas closest to the canister to those at the host rock contact. These tests were performed using different bentonites (MX-80, Bara-Kade, FEBEX, BCV), cell dimensions (height from 10 to 50 cm, diameter from 7 to 30 cm), initial buffer conditions (powder, pellets, water contents from 6 to 17%, dry density from 0.9 to 1.6 g/cm3) and testing protocols (heating followed by hydration, hydration followed by heating, simultaneous heating and hydration). The tests can be considered medium-scale ones, since their dimensions are relevant for the usual barrier thickness envisaged by most repository concepts. In all of them the heater plate simulating the canister surface was placed at the bottom (at temperatures 140-150°C) and the temperature on top was regulated either at 20°C or at room temperature. Hydration water (deioinised, glacial or saline) was supplied through the top at a low injection pressure. Out of the TH tests included in this Subtask, test HEE-B reproduced the conditions of a large-scale in situ experiment (HE-E at Mont Terri), whereas the others were not representative of any particular disposal concept.

The second group of tests aimed at assessing how the high temperatures close to the heater could affect the hydration rate and swelling development. Thus, they were carried out under isothermal high temperatures (120, 140°C) with FEBEX bentonite compacted at dry density 1.6 g/cm3 with its hygroscopic water content.

The tests are described in detail in this report (or in cited published literature) and the results concerning online measurements during operation (temperature, relative humidity, pore pressure, axial and radial mechanical pressures, water intake) and postmortem physical state of the bentonite (water content, dry density) are presented herein. The following conclusions could be reached:

- The testing sequence (heating before or after hydration) impacts the thermo-hydro-mechanical evolution of the system.
- Hydration under thermal gradient can progress even if the water injection pressure is very low, but full saturation may take much longer than under lower isothermal conditions. However, the tests reported did not allow to check if full saturation of the areas closest to the heater is possible,

either because the tests were too short or because of experimental artefacts, namely evaporation through the cell sensors' inlets.

- Relevant radial swelling stresses –associated to the increase in water content– were recorded during hydration under high temperature, higher when diluted water was used instead of saline one.
- The postmortem state was linked to the testing protocol:
    - In those tests in which no full saturation was reached (because there was not an initial saturation phase), significant gradients in the water content and dry density distributions developed in the bentonite, with higher water contents close to the hydration surface, where the dry density was lower.
    - Only in the test in which bentonite –with a very low dry density– was first saturated and then heated, the final dry density and water content were homogeneous in most of the bentonite column.
    - n the isothermal tests, where hydration took place through the bottom of the samples, the dry density was lower on the bentonite block side opposite to the hydration surface, where also the highest water contents were measured. This distribution likely results from the upwards vapour movement, which concentrated on top of the cell and would also trigger bentonite swelling and increase in porosity.

The tests performed with pellets showed trends of behaviour similar to those expected for compacted bentonite.

3.3.2 Modelling (D10)

This section presents a summary of modelling activities within EURAD WP7 HITEC (Influence of temperature on clay-based material behaviour). Three teams have been involved, namely CIEMAT (UPC), SURAO (CTU and CU) and VTT.

CIEMAT (UPC) developed a constitutive model as a THM extension of an existing double structure elastoplastic model that incorporates the effects of temperature. Thermal-induced strains are considered reversible at this stage of model development. The numerical simulations of the benchmark experiment defined in MS130 were performed, while the material parameters were calibrated either from bentonite tested at high temperature or by back-calculations. The model reproduced quite well the main features observed during the test of the heated column, i.e. the evolution of temperature, relative humidity, water intake and axial pressure throughout the test. However, some discrepancies have been found between the numerical results and the laboratory data regarding the final distribution of dry density and saturation.

SURAO (CTU and CU) developed and validated the THM hypoplastic model for bentonite. Its formulation has already been available at the start of EURAD project, however, within EURAD, the model was be calibrated to represent high temperature experiments and several of its components (such as the formulation of water retention curve and formulation for microstructural collapse) were further developed. The model has been used in simulations of benchmark experiment performed at CTU. Good fit was demonstrated for temperature evolution. Problematic aspects remaining to be solved were simulations of extremely low dry density bentonite, adopted in CTU benchmark 1, and vapour generation during heating above 100°C in CTU benchmark 2, which led to calculation divergence.

Finally, VTT prepared a numerical model of the thermal conditions in Olkiluoto disposal site in Finland to obtain a realistic view of the expected thermal conditions. The model includes thermal conduction through the disposal site components surrounding one disposal hole, but also thermal radiation was considered over gas filled gaps within the disposal canister. For simulations, VTT proposed to use

Varied Multiplicative Processes model developed within the scope of large deformation plasticity. Simulations of Olkiluoto disposal site are to be finished once the experimental work for the mechanical model dependencies on the temperature by VTT has been finished.

4. Task 4: Reporting and impact

4.1.1 Safety case guidance

HITEC aimed to develop and document improved THM understanding of both host rock and buffer clay-based materials exposed to temperatures above 100 °C for extended durations. The WP evaluated whether or not elevated temperature limits of 100 – 150°C are feasible and safe for a variety of geological disposal concepts for high heat generating wastes.

Observations

- It has been shown that the effect of temperature (up to 100°C) modifies some properties of bentonite but they keep in values acceptable for complying with the safety functions.
- There are inconsistencies in the results and a lack of full understanding with respect to HM properties of bentonite at temperature higher than 100°C also because of challenging experimental conditions.
- Less work has been done on the effect of temperature on the water retention curve and thermal conductivity.
- Concerning the modelling of the buffer behaviour, it is considered that the THM formulations developed and validated for temperatures below 100°C can be extended without modifications to temperatures above that value.
- For the clay host rock previous knowledge indicate that an increase in temperature due to the presence of heat-emitting wastes will induce strong and anisotropic THM coupled responses within the clay. Thermal expansion of pore water and thermal-induced decrease of clay strength are to be considered as a potential risk for failure.
- In contrast, thermal-induced plasticity, swelling and creep of clay are likely beneficial to the sealing of fractures. Considering anisotropic properties of clay in the numerical simulations improves significantly the predictive capability of the numerical models.

Guidance for Safety Case Development with focus on safety assessment and optimization is the D7.11, (Leupin et al., 2024).

The input was collected from 8 WMOs

- ANDRA
- ENRESA
- Nagra
- NWS
- ONDRAF/NIRAS
- POSIVA
- SKB
- SÚRAO

Key messages from WMO's in D7.11 are:

ONDRAF/NIRAS: […] if the selected host rock turns out to be a poorly indurated clay, there is little margin for optimisation of the thermal design […] The main benefits from HITEC to the Belgian programme are related to Task 2. In particular, the modelling benchmark performed for the large scale in situ heater test PRACLAY in HADES allowed to confirm and strengthen confidence in our understanding of the THM behaviour of the Boom Clay.

POSIVA: It has been identified in HITEC that even after relatively high-temperature treatment (~150 °C) bentonite maintains most (if not all) its properties. This highlights that in reality the buffer is more reliable than assumed in safety case and gives more certainty on buffer working as intended even if high temperatures are reached.

SKB: There are however also observations that are not fully understood. These would need further explanation but are most likely not critical for the long-term performance of the barrier.

SURAO: The results of the HITEC project show that the temperature limit of 95°C for bentonite is possibly too conservative and no significant alteration of montmorillonite should not be the case with temperatures up to 150°C

4.1.2 Final reporting

The final reporting of HITEC consists of 12 deliverables: two for initial and final SotA, four clay host rock and four bentonite buffer reports, Safety case guidance and this final report (Table 1). In addition, HITEC has published tens of scientific articles and conference presentations.

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