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Deliverable 6.5.

Final workshop of EURAD-GAS and -HITEC: compilation of presentations

Work Package GAS

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Executive summary

In the framework of EURAD, the European Joint programme on Radioactive Waste Management (2019-2024), two work packages have addressed the behavior of clayey materials in the context of geological disposal of radioactive waste:

- EURAD-GAS was devoted to the mechanistic understanding of gas transport in clayey materials,
- EURAD-HITEC studied the influence of temperature on clay-based material behavior.

Both work packages studied two types of clayey materials: geological (potential host rocks) and engineered (bentonites, which are typically used in engineered barriers for their sealing capacity). They both performed experimental and numerical studies, at small (laboratory) and large (in situ) scales, and have conceptualized the knowledge at repository scale with input into geological repository design and post-closure safety cases.

It was therefore decided to organize a workshop common to the two work packages at the end of the project. The objective of this workshop was twofold:

- Highlight the progress within EURAD in terms of knowledge on issues related to temperature and gas transport.
- Show how the results of EURAD-GAS and EURAD-HITEC can be used by end-users to support repository design and/or safety cases.

This final EURAD-GAS and -HITEC workshop provided an overview of the progress made in understanding heat transfers, water and gas transport and their consequences in terms of stress and strain evolution in a geological repository. It also provided an opportunity to disseminate the results and expected impacts of the two work packages to a wide audience.

The workshop was primarily targeted at end-users from institutions active in EURAD and beyond. This workshop gathered nearly 50 participants in person and more than 10 online. These were either researchers involved with EURAD-GAS or EURAD-HITEC (RE), and members of waste management organizations (WMO) and technology support organizations (TSO).

At the end of the workshop, the participants had an overview of what had been done in the EURAD-GAS and EURAD-HITEC research programs. They had met a number of key researchers in the field of thermo-hydro-mechanical (THM) properties of clayey materials and gas transport in the context of geological disposal, thus fostering information exchange and cooperation within the geomechanics community. In particular, participants were able to:

- Understand the main conclusions of EURAD-GAS and EURAD-HITEC,
- Evaluate the application of these results to geological disposal repository design and post-closure safety cases.

This document includes the slides presented at the workshop. It also briefly summarizes the context and main results of EURAD-GAS and EURAD-HITEC.

Table of content

1. Introduction

The Final GAS & HITEC workshop is organized within the framework of EURAD, the European Joint programme on Radioactive Waste Management (grant agreement No 847593). The objectives of EURAD include the development of new knowledge and consolidation of existing knowledge for the safe start of operation of the first geological disposal facilities for spent fuel, high-level waste (HLW), and other long-lived radioactive waste, and supporting optimization linked with the step wise implementation of disposal. This workshop is related in particular to two of the Work Packages of the EURAD Joint Programme, namely the EURAD-GAS and EURAD-HITEC, dealing respectively with "*Mechanistic understanding of gas transport in clay materials*" and "*Influence of temperature on clay-based material behavior*".

1.1 Objective and target audience

EURAD-HITEC deals with thermal impact and EURAD-GAS concerns gas transfer, both in the context of geological disposal of radioactive waste. These two work packages share the same community of geomechanics and multi-physical coupling. This workshop allows the attendees to have an overview of the step forward of these two work packages in terms of understanding of heat transfers, water and gas transport and consequences in term of stress and strain evolution in a geological repository. These investigations involve clayey materials such as the host rock or bentonite which is typically used in engineered barriers for its sealing capacity. It addresses both experimental and numerical investigations, at small (laboratory) and large (in situ) scale, but also conceptualization of knowledge at repository scale and input to the geological repository design and post-closure safety cases.

This final GAS/HITEC workshop offered the opportunity to disseminate the results and expected impacts of the two work packages in a broad audience. The aim of this workshop was twofold:

- Highlight the progress within EURAD in terms of knowledge on issues related to the temperature and gas transport.
- Show how the results of EURAD-GAS and EURAD-HITEC can be used by end-users to support repository design and/or safety cases.

The workshop was primarily targeted at end-users from institutions active in EURAD and beyond. This workshop gathered together nearly 50 participants in person and more than 10 online. These were either researchers involved with EURAD-GAS or EURAD-HITEC (RE), and members of waste management organizations (WMO) and technology support organizations (TSO).

At the end of the workshop, the participants had an overview of what had been done in the EURAD-GAS and EURAD-HITEC research programs. They had met a number of key researchers in the field of thermo-hydro-mechanical (THM) properties of clayey materials and gas transport in the context of geological disposal, thus fostering information exchange and cooperation within the geomechanics community. In particular, participants were able to:

- Understand the main conclusions of EURAD-GAS and EURAD-HITEC,
- Evaluate the application of these results to geological disposal repository design and post-closure safety cases.

1.2 Workshop program

The workshop was organized on 26 April 2024 at the Pullman Bucharest World Trade Center of Bucharest in Romania. It was divided into three sessions. The workshop was divided into nine presentations given by partners from the two work packages, either academics, scientists from research entities and people from national waste management organizations. The programme of the workshop was as follows:

Welcome		**Séverine Levasseur and Markus Olin**
Session 1: Temperature		**Chair: Markus Olin**
9:00	Effect of high temperature on bentonite properties and processes	Jiří Svoboda
9:30	Measuring clayey host rock behavior at high temperatures	Dragan Grgic
10:00	Modeling of clayey host rock mechanics at elevated temperature	Christophe de Lesquen and Arnaud Dizier
10:30	**Break**	
Session 2: Gas		**Chair: Séverine Levasseur**
11:00	Introduction: the EURAD-GAS work package	Séverine Levasseur
11:30	Key results on gas diffusion	Elke Jacops
12:00	Key results on gas advection	Laura Gonzalez-Blanco
12:30	**Lunch**	
Session 3: Messages to end-users: Input of EURAD-GAS and EURAD-HITEC to the repository design and the safety case		**Chair: Christophe de Lesquen**
14:00	Key messages for treatment of high temperature	Alexandros Papafotiou and Olivier Leupin
14:30	Key messages for treatment of gas transport	Jacques Wendling and Paul Marschall
15:00	Final discussion and closing of the meeting	All
16:00	**Closure**	

1.3 Structure of the document

Chapter 2 and Chapter 3 contain the context and main outcomes of respectively EURAD-GAS and EURAD-HITEC. The slides presented during the workshop, which constitute the core of this document, are provided in Chapter 4. They are also available on ProjectPlace, in folder https://service.projectplace.com/#/project/1763332387/documents/364744379). Appendix A lists the participants and Appendix B the bibliography.

2. EURAD-GAS

2.1 Context

Considerable amounts of gas can be generated in a geological repository for radioactive waste. The largest fraction of the gas is expected to be hydrogen produced through the anaerobic corrosion of steel and reactive metals present in the waste, in their packaging and in the engineered barrier system[1] (EBS). Radiolysis and the degradation of organics also produce gas. Even though the gas production processes are generally slow, it is important to verify that these will not be detrimental to the good functioning of the disposal system. The low permeability of clays, which is favorable to the containment function of a repository, also limits the evacuation of the generated gas. It is possible that gas could be produced at a faster rate than it can be removed through the EBS, resulting in the development of a pressurized gas phase within the repository. If the pressure of accumulated gas in the repository is too high, gas could then escape from the repository to the host rock by creating gas-specific pathways through the EBS and/or the host rock. In case the gas contains volatile radionuclides, its potential release to the biosphere is an area that needs specific considerations by the organizations in charge of developing a geological repository and therefore requires robust underpinning knowledge.

The main objectives of the work package, called EURAD-GAS, were:

- To improve the mechanistic understanding of gas transport processes in engineered and geological clayey materials, their couplings with the mechanical behavior and their impact on the properties of these materials.
- To evaluate the gas transport mechanisms that can be active at the scale of a geological disposal system and their potential impact on barrier integrity and repository performance.

EURAD-GAS has produced eight deliverables in addition to this one:

- Three thematic technical reports with detailed scientific achievements: *Gas transport mechanisms: diffusion, retention and advection processes* (Deliverable 6.7, Task 2) (Jacops and Kolditz, 2024), Barrier *integrity: gas-induced impacts and model-based interpretation* (Deliverable 6.8, Task 3) (Marschall *et al.*, 2024) and *Modelling of a generic geological disposal: evaluation of various approaches to model gas transport through geological disposal systems* (Deliverable 6.9, Task 4) (Wendling *et al.*, 2024). These three comprehensive reports detail all the work carried out by each partner during EURAD-GAS.
- Two state-of-the-art reports, with the full integration of the shared understanding of the EURAD-GAS partners on gas transport processes and their controls in clayey materials with guidance on what could be the controls of gas and its impact at the repository scale: *Initial state of the art on gas transport in clayey materials* (Deliverable 6.1) (Levasseur *et al.*, 2021) and *State of the art on gas transport in clayey materials – Update 2023* (Deliverable 6.2) (Levasseur *et al.*, 2024b).
- A concluding report, *Achievements of EURAD-GAS* (Levasseur *et al.*, 2024a).

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[1] The EBS comprises all man-made components, including thus the lining. In the French concept, most of the hydrogen production is actually expected to come from the corrosion of the metallic reinforcement of the concrete lining around the access galleries and large ILW cells.

2.2 Impacts of EURAD-GAS and perspectives

EURAD-GAS has increased confidence in the overall understanding of gas behavior in clayey materials, building on the FORGE EC project and beyond. This has in turn improved its integration into the conceptualization process for the different components of a disposal system, supporting and justifying the use of robust evaluation approaches. Overall, the discussion among all members of EURAD-GAS, including research entities, technical support organizations, and waste management organizations, has helped to strengthen the expert judgment at the end of FORGE: gas is not a showstopper for geological disposal, but rather requires effective management of uncertainties.

The impacts of EURAD-GAS are detailed in the next sections, in terms of implementation needs (Section 2.2.1), safety (Section 0), and scientific and technical knowledge (Section 2.2.3).

2.2.1 Regarding implementation needs for geological disposal

EURAD-GAS has produced documents for implementers that may inspire design measures to further reduce the gas impact, or the uncertainties associated with gas transport through geological disposal systems. Two state-of-the-art reports have been written. The first one presents some fundamentals on gas transport in clayey materials (Levasseur *et al.*, 2021) while the second focuses on key messages for end-users such as program managers (Levasseur *et al.*, 2024b).

2.2.2 Regarding safety of geological disposal systems

EURAD-GAS has provided experimental evidence on the processes involved in gas transport throughout a disposal system and on the effects of these processes on barrier materials (Jacops and Kolditz, 2024; Marschall *et al.*, 2024). This evidence can be referred to by national programs in the arguments supporting claims about long-term safety of a geological system. EURAD-GAS had also collected elements that make it possible to identify the inherent strengths and limitations of various approaches for the treatment of gas in safety cases and to assess their suitability in different contexts, recognizing that this may depend on the disposal system that is being evaluated (host rock/design) or even the advancement of the (national) program (Wendling *et al.*, 2024). Similarities of approaches between national programs were identified and the rationale behind differences explained (Levasseur *et al.*, 2021).

2.2.3 Regarding increased scientific and technical knowledge

EURAD-GAS has succeeded in bridging the gap between experimentalists and modelers. Building on the lessons learned from the FORGE EC project, modelers were embedded with the experimentalists to encourage dialogue in the design of experiments and the development of shared conceptualizations of the observed behavior (Jacops and Kolditz, 2024; Marschall *et al.*, 2024). By doing so, EURAD-GAS has built confidence and extended the scientific bases on the fundamentals of gas transport in clayey materials. It has confirmed that the fundamental gas transport mechanisms that can develop in different clays are similar. Because a wide enough, but realistic, range of conditions were explored for representative clayey materials, EURAD-GAS has provided data which are of relevance for all disposal systems that include clayey barriers. Testing over a range of conditions spanning low (diffusion) to high (advection) gas generation rates, a better understanding of processes has been acquired which then has broader end-users' appeal. This understanding is described in the final technical reports (Jacops and Kolditz, 2024; Marschall *et al.*, 2024; Wendling *et al.*, 2024) and is summarized in the next subsections.

2.2.3.1 Diffusion and adsorption

Diffusion

- Diffusion coefficients of several dissolved gases (that can be used as proxy for hydrogen) are available for a wide range of water-saturated clayey materials. Various types of laboratory setups exist for determining the diffusion coefficient over a wide range of water-saturated clayey materials and under various mechanical conditions. The reproducibility of these tests is high.
- Diffusion of dissolved gas is now well understood in water-saturated clayey materials. A clear correlation between permeability and diffusion coefficient exists. Relationships between diffusion coefficient and permeability are established for different clayey saturated materials over a wide range of mechanical conditions. In practice, it means that knowledge of permeability can give a first estimate of diffusion coefficient. However, this relationship appears to be material dependent. Work is still going on to determine how the relationship permeability-diffusion coefficient for a given material can be linked to its mineral composition and so explain differences of diffusion coefficients between clays. In all studied clays, it is observed that variations of permeability over several orders of magnitude result on variations of dissolved gas diffusion coefficient of less than one order of magnitude.

Adsorption

- Issues on gas adsorption on clayey materials were cleared out. New gas adsorption tests have been performed under well-controlled conditions. These have led to the conclusion that the capacity of clayey materials for gas sorption is very low in the repository conditions tested during EURAD-GAS and has been overestimated in the past due to experimental artifacts.

2.2.3.2 Advective transport

The experimental program has improved the experimental setups previously developed (e.g., in FORGE EC project). Notable progress was made in visualization techniques (postmortem but also near-real time during experiments).

- For the materials and conditions examined within the laboratory program of the EURAD-GAS, tests evidence a dilatant behavior of the clayey materials associated to gas passage above a certain threshold. For these tests, dilatancy-controlled gas pathways tend to be multiple, taking advantage of local defects or planes of weakness within the materials. Nevertheless, these pathways do not affect permanently the water permeability which stays in the same range before and after gas breakthrough events thanks to self-sealing capacity of clayey materials. Interestingly, experiments that make it possible to measure the amount of water expulsed from the material being tested showed very little amount of water compared to the volumes of gas that passed through the material. For all samples that were initially saturated or close to saturation, high saturation degrees were preserved after testing.
- The coupling between gas transport and the mechanical behavior of the clayey material is confirmed. It is however recognized that breakthrough pressure (the pressure at which gas passage is detected at the outlet of an experimental setup) depends at least as much on the experimental initial and boundary conditions as on material properties. Hence, good understanding of – and transparency about – the specific conditions imposed by each setup is essential for correct interpretation of the experiments and use of their results (idem for postmortem interpretations).

Significant progress was made on the process-level modeling front.

- A variety of extensions of the classical visco-capillary process models, enhanced with mechanical features, have been developed and successfully tested with new experimental data sets.
- Process-level models that combine pathways activation and development mechanisms at the microscopic scale and the evaluation of field parameters and conditions at larger scale are progressively gaining more traction. These complement the more traditional approaches such as the use of coupled multiphase flow and mechanical continuum models with transport parameters that empirically depend on deformations.
- However, while most of the process-level models can generally be used to reproduce (fit) experimental results such as those obtained in EURAD-GAS and before with appropriate choice of parameters, predictive capabilities are still perceived as limited. These models are thus currently used mostly as a support to interpretation and for testing hypotheses on gas transport mechanisms.

2.2.3.3 Enhanced capabilities for assessment at repository scale

Next to the experimental evidence and process-level model developments gained from EURAD-GAS, attention was also given to the stepwise integration process of this scientific knowledge. This supports the conceptualization at the scale of a disposal system and can be used to justify the use of simpler evaluation approaches at that scale. For instance, if calculations performed at the scale of components of a disposal system with models that can resolve couplings between gas transport and the mechanical behavior of the barriers yield gas pressures that would not affect these barriers much mechanically, a two-phase flow approach can be used to obtain realistic orders of magnitude for gas pressures and transport rates through the system as a whole. This can be, in turn, used to evaluate the transport and release of gaseous radionuclides which are carried with the inactive gas.

More broadly, for the different concepts considered within EURAD-GAS in the studied clayey host rocks, the main findings of EURAD-GAS with respect to scientific basis and capabilities for assessment at repository scale can be summarized as follows:

- Evacuation of gas from the disposal system should take place
    - as dissolved gas or in gas form, through the EBS (backfill, seals and linings) and the EDZ, and their interfaces,
    - as dissolved gas only throughout the host rock, by diffusion.

If these conditions are respected:

- In water-saturated conditions, mobilization of water-soluble radionuclides by gas is expected to be very low because little or no water displacement is associated to the evacuation of gas.
- Gaseous radionuclides that would not completely dissolve into the pore water upon release from the waste form can be carried toward the shafts and/or ramps along with the inactive gas (generated in much larger quantities). However:
    - The duration of the transport from the gas source to the shafts and/or ramps may take several hundreds to several thousand years (order of magnitude, design dependent) and only radionuclides with half-lives around this duration or higher may present a significant concentration in the gas phase when arriving in the upper formations.
    - All along the gas pathways, part of the gaseous radionuclides will also dissolve (as inactive gas also does) into the pore water present in the surrounding materials.

2.3 Future perspectives

Based on the FORGE EC project, EURAD-GAS has made a major step forward on the mechanistic understanding of the transport of gas in clayey materials. However, further research is needed to address remaining questions.

Regarding the scientific basis, it is recommended to perform the following actions:

- Expand experimental databases (mainly gas transport properties and, when relevant, relationship between properties), by conducting experiments under conditions that are representative of repository conditions.
- Develop and share best practices in terms of sample handling and experimental protocols, in line with the efforts initiated by Nagra during EURAD-GAS with the support of CIMNE/EPFL/BGS (including the use of visualization techniques).
- Strengthen dialogue between modelers and experimenters in the design of experiments and the development of shared conceptualizations of observed behavior.
- Further develop coupled microscopic models to refine small-scale process understanding.
- Develop a portfolio of models at different scales (microscopic, centimeter, component, repository) (stepwise abstraction process) and assess their applicability. Having a range of models available (each with their advantages and limitations, but always based on a physical basis) allows for the selection of the most appropriate one(s) for a particular disposal system.

Regarding end-users' needs, organizations involved in radioactive waste management should continue to exchange information. This includes:

- Sharing and further developing best practices for dealing with gas transport processes and impacts. Efforts are needed to apply the knowledge gained from small-scale experiments appropriately at the repository scale. Gas requirements evaluated through modeling for the whole disposal system need to be broken down into requirements at lower levels of design.
- Developing common strategies to ensure that gas transport requirements are compatible with all other requirements of the geological disposal system and are well integrated in the design and optimization processes.

3. EURAD-HITEC

3.1 Context

Most safety cases for the disposal of spent fuel in a geological repository limit the temperature at the surface of the disposal package to maximum 100°C. Allowing a higher temperature limit could have significant advantages such as allow disposal of higher enrichment/burn-up spent fuels and shorter interim storage/cooling requirements. EURAD-HITEC aimed to improve thermo-hydro-mechanical (THM) description of clayey materials at elevated temperatures. The clayey host rocks were studied under saturated conditions under 120°C, while bentonites, potentially used as buffers in many disposal concepts, were studied both in saturated and unsaturated conditions under 150°C.

3.2 Key conclusions

3.2.1 Clayey host rock

The heat generated by waste must not affect the favorable properties of the host rock, especially its transport properties, for containment. It is important to assess if the overpressure generated by the thermal expansion of pore water and the solid rock skeleton may have deleterious consequences or not. In the far field, induced rock damage and reactivate fractures/faults should be avoided. In the near field, fracture opening or extension of the excavation damaged zone, altering the permeability is not allowed.

The characterization of in situ THM behavior of the clayey host rock, in both near and far field of a repository, was part of EURAD-HITEC experimental program. Boom Clay (BC), Callovo-Oxfordian (COx) claystone and Opalinus clay (OPA) were the different clayey host rocks studied.

For the near field, self-sealing tests were performed (Figure 1). EURAD-HITEC showed that a higher calcite content decreases the self-sealing efficiency of clay. Self-sealing is faster for tighter cracks, without clear effect of the orientation of the bedding planes. As already shown in TIMODAZ EC project, temperature does not play either a significant role on the self-sealing capacity of clays.

For the 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 negative impact on the short-term resistance to failure of the COx claystone.

The following technical reports of EURAD-HITEC describe this understanding: D7.3 (Grgic, Bésuelle *et al.*, 2024), D7.4 (de Lesquen et al., 2024) and D7.5 (Grgic, Imbert *et al.*, 2024).

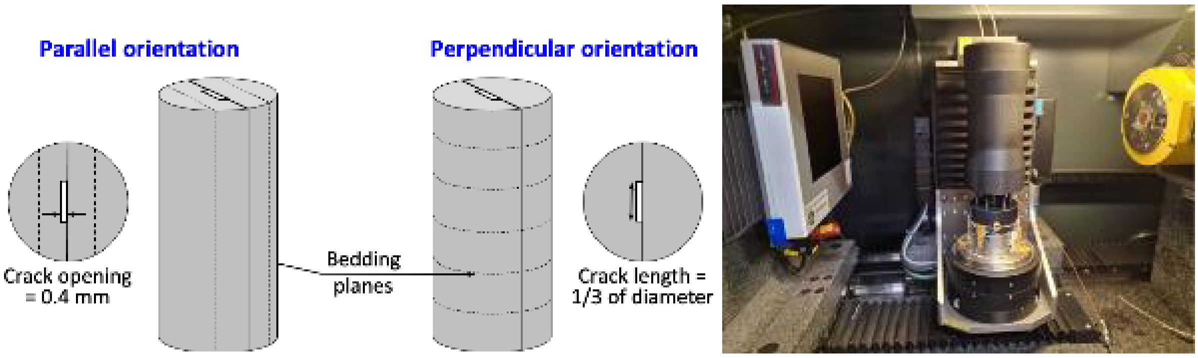


Figure 1 – The experimental setup applied for the study of self-sealing in clayey host rock.

3.2.2 Bentonite buffer

Regarding bentonite buffers, it is expected that the elevation of temperature results in strong evaporation near the heater and vapor movements toward the external part of the buffer. As a consequence, part of the barrier, or all of it, depending on the particular disposal concept, may remain unsaturated and under high temperatures during long periods of time. Moreover, the high temperature gradient (and pore pressure) even crossing boiling point of water may lead to several adverse effects such as Sauna effects. To evaluate whether an increase of temperature is feasible and safe, experimental works were done in EURAD-HITEC on MX-80, FEBEX and BCV bentonites for a range of temperature reaching 130-150°C.

EURAD-HITEC results show that, for bentonite buffer, proving that higher temperatures than currently accepted are suitable even for current disposal concepts. It increases safety margins and gives greater credibility to the design (e.g., if it is proven to work for 130°C then for 100°C it is safe). This type of optimization could be used to increase thermal limits on the bentonite buffer, reducing the footprint of the facility.

No new processes were identified in the frame of EURAD-HITEC, but swelling, swelling stress formation and water conductivity were studied in detail over 100°C temperatures (Figure 2). Relationships delineated 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 programs, in both Ca- and Na-bentonite have found evidence that, while 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 behavior for repository design are nevertheless recommended to confirm or not this observation.

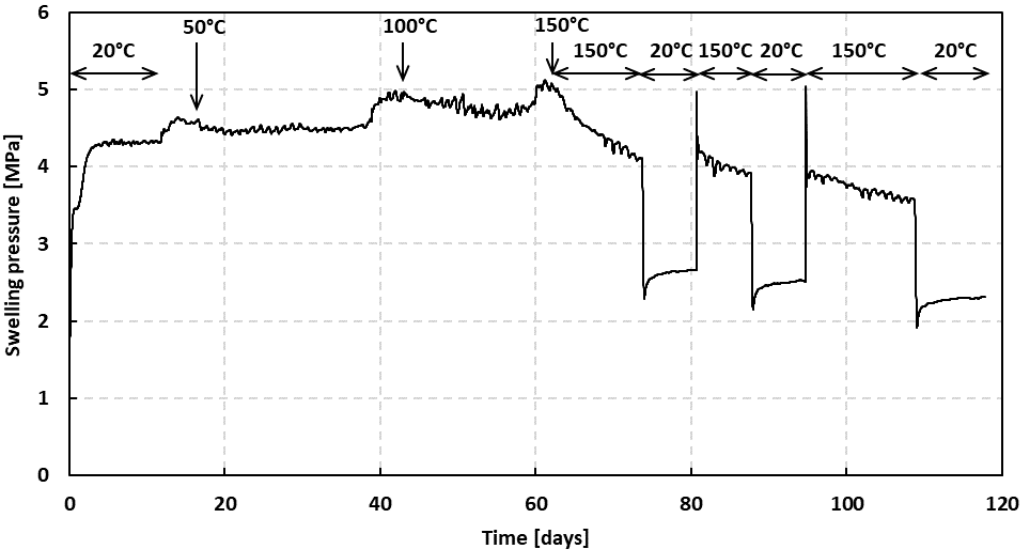


Figure 2 – Effect of cyclic temperature change on swelling pressure.

The following technical reports of EURAD-HITEC describe this understanding: D7.7 (Svensson et al., 2024), D7.8 (Graham et al., 2024) and D7.9 (Villar et al., 2024).

3.2.3 THM modeling benchmark on the effect of heating on clay formations

In complement to the experimental program, a series of benchmarking exercises were performed in EURAD-HITEC based on the concepts of radioactive waste disposals developed by Andra, ONDRAF/NIRAS (EURIDICE) and Nagra. The benchmark was divided into 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 behavior of clayey rocks (Callovo-Oxfordian (COx) claystone, Boom Clay and 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 (Figure 3). Some triaxial compression tests performed in the experimental part of the project were then studied. Finally, two full-scale in situ heating experiments were modeled: the ALC1605 experiment performed in the COx claystone, and the PRACLAY experiment in the Boom Clay.

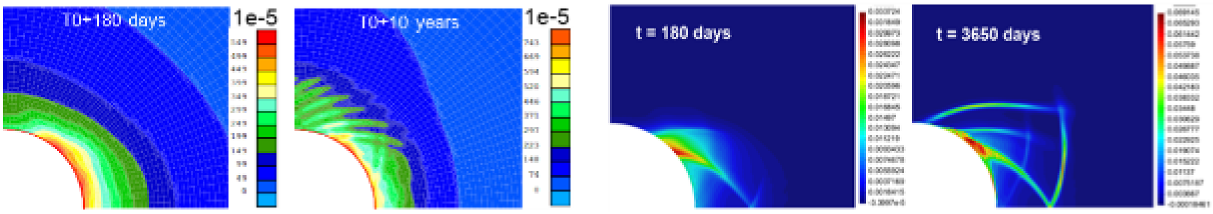


Figure 3 – Plastic shear strain at the start and at the end of the heating stage – ULg and UPC models.

In the first exercise, focusing on the effect of heating in the near field of a high-level waste (HLW) cell, very consistent results were obtained in the elastic isotropic case. More variations were observed in the pore pressure and stress predictions in the anisotropic case, especially in the COx and Opalinus clay. These variations were most likely due to differences in the THM formulations and assumptions made in the different codes and to some mesh dependency. All the models were able to reproduce the development of the excavated-damaged zone (EDZ), matching the shape observed in the underground laboratories. Some variations appeared on the extent of the EDZ, but all models indicated a limited effect of heating on its evolution.

The far-field benchmark was run only on a COx case. As for the near-field case, the responses vary near the gallery, but very consistent results were obtained at mid-distance between two neighboring galleries (Figure 4). An anisotropic poro-elastic behavior is known to provide a good prediction of the evolution of both temperature and pore pressure. These results increase therefore the confidence one can have in this type of model and show the robustness of the modeling approach used to design the repositories. In addition, this project gave an opportunity to improve some of the codes or to validate some recent developments.

Triaxial compression tests performed under elevated temperature by the ULorraine on COx samples were modeled. The modeling of the heating phase under undrained conditions revealed the generation of overpressures when fast heating rates were applied, inducing some damage in the samples. These numerical results 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. Some models were updated to take into account this strength decrease with temperature.

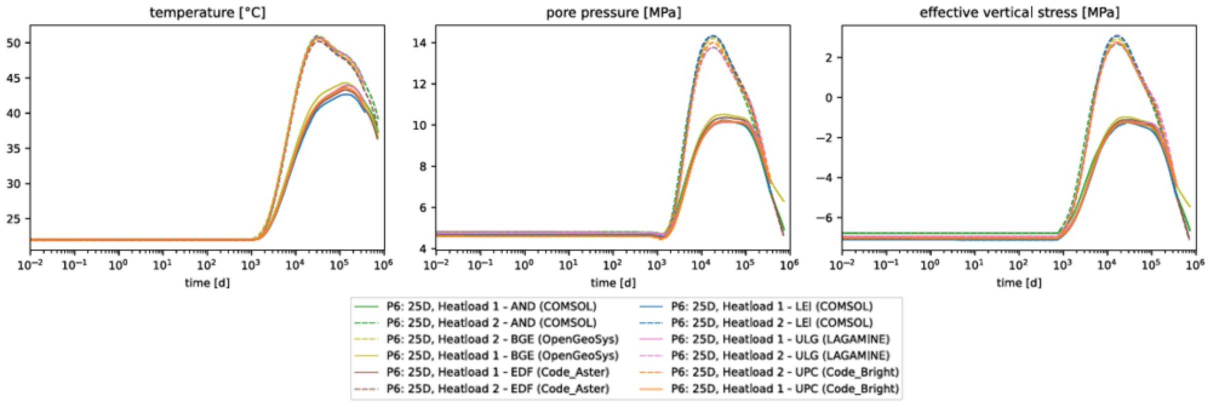


Figure 4 – Comparison of temperature, pore pressure and Terzaghi effective vertical stress at mid-distance between two neighboring cells for two heating scenarios.

The last step of the benchmark consisted in modeling two large-scale in situ heating experiments: ALC1605 in the COx claystone and PRACLAY heater test in the Boom Clay. In both cases, the teams successfully managed to reproduce the anisotropic response of the clayey host rocks to excavation and heating. In particular, the evolutions of temperature and pore pressure were well modeled 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.

The following technical report of EURAD-HITEC describes this understanding: D7.6 (de Lesquen et al., 2021).

3.3 Safety case guidance

The outcomes of EURAD-HITEC were finally used to provide guidance for safety case development and repository optimization for WMOs. To ensure the long-term safety of deep geological disposal, Waste Management Organizations (WMOs) formulate safety related claims pertaining to their technical and natural barriers. These high-level claims that explain why safety is given are typically substantiated by compelling arguments that explain why these barriers are performing as required. These arguments, in turn, draw strength from a plethora of evidence, including experimental studies, empirical knowledge, the study of natural analogs, and modeling evidence.

Claims associated with technical and natural barriers, especially those subjected to high temperature gradients, demand a repository specific understanding of thermal transients and their couplings. Consequently, building a specific body of arguments becomes fundamental for the safety case of every disposal system.

The needed evidence for supporting the claims comprises an array of experimental and empirical research, insights derived from natural analogs, and modeling-based findings. This extensive evidential foundation often finds its origins in collaborative initiatives like EURAD-HITEC and similar international projects.

The strength and reliability of the evidence provided hinge upon its capacity to accurately represent the anticipated conditions within a geological repository. Therefore, it is essential to establish a well-constrained evolutionary path (“storyboard”) for thermal, hydraulic, and mechanical (THM) conditions before specifying the parameters for testing. By gaining a comprehensive understanding of the evolution of safety-related properties in both technical and natural barriers, we can reduce unnecessary conservatisms and allow for optimizations for various aspects of the repository, from individual components to the layout of the entire facility.

In conclusion, the robust substantiation of safety claims is an indispensable aspect for a convincing safety case. This process hinges on a diverse and comprehensive body of evidence, requiring an understanding of thermal transients, the evolutionary path of THM conditions, and the ability to reduce conservatism, ultimately enabling the optimization of key components and repository designs. This concerted effort contributes significantly to the safeguarding of our environment and future generations.

The following technical report of EURAD-HITEC describes this understanding: D7.10 (de Vasconcelos et al., 2024).

4. Workshop presentations

The presentations are sorted by session.

Welcome

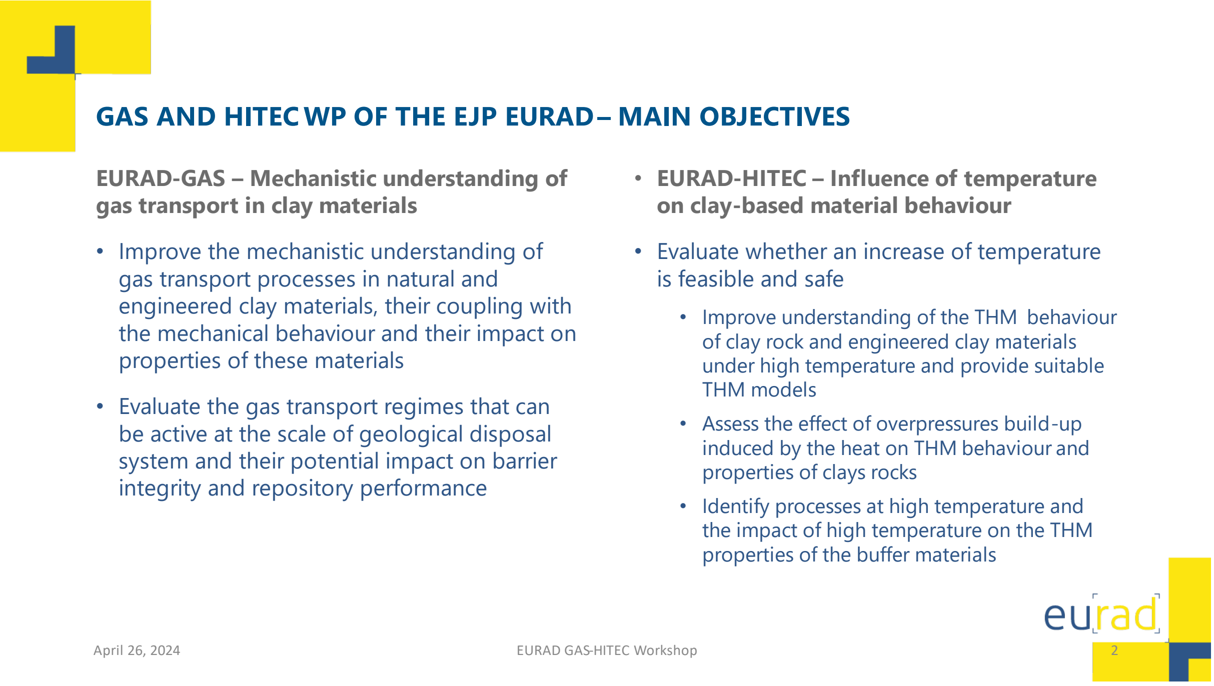
EURAD GAS-HITEC WORKSHOP

WELCOME

Mexico & Seoul Room, Pullman Hotel, Bucharest, Romania

26 April 2024 • Séverine Levasseur & Markus Olin

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°847593

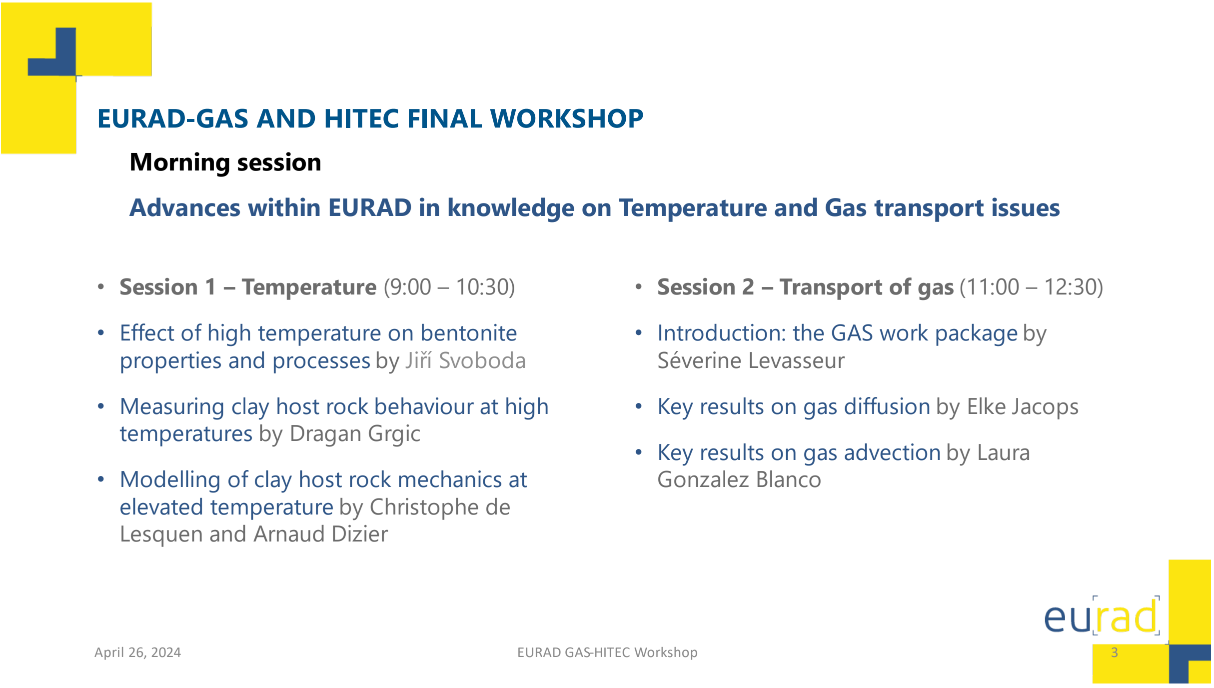


GAS AND HITEC WP OF THE EJP EURAD – MAIN OBJECTIVES

EURAD-GAS – Mechanistic understanding of gas transport in clay materials

- Improve the mechanistic understanding of gas transport processes in natural and engineered clay materials, their coupling with the mechanical behaviour and their impact on properties of these materials
- Evaluate the gas transport regimes that can be active at the scale of geological disposal system and their potential impact on barrier integrity and repository performance

- **EURAD-HITEC – Influence of temperature on clay-based material behaviour**
- Evaluate whether an increase of temperature is feasible and safe
  - Improve understanding of the THM behaviour of clay rock and engineered clay materials under high temperature and provide suitable THM models
  - Assess the effect of overpressures build-up induced by the heat on THM behaviour and properties of clays rocks
  - Identify processes at high temperature and the impact of high temperature on the THM properties of the buffer materials



EURAD-GAS AND HITEC FINAL WORKSHOP

Morning session

Advances within EURAD in knowledge on Temperature and Gas transport issues

- **Session 1 – Temperature** (9:00 – 10:30)
- Effect of high temperature on bentonite properties and processes by Jiří Svoboda
- Measuring clay host rock behaviour at high temperatures by Dragan Grgic
- Modelling of clay host rock mechanics at elevated temperature by Christophe de Lesquen and Arnaud Dizier

- **Session 2 – Transport of gas** (11:00 – 12:30)
- Introduction: the GAS work package by Séverine Levasseur
- Key results on gas diffusion by Elke Jacops
- Key results on gas advection by Laura Gonzalez Blanco

EURAD-GAS AND HITEC FINAL WORKSHOP

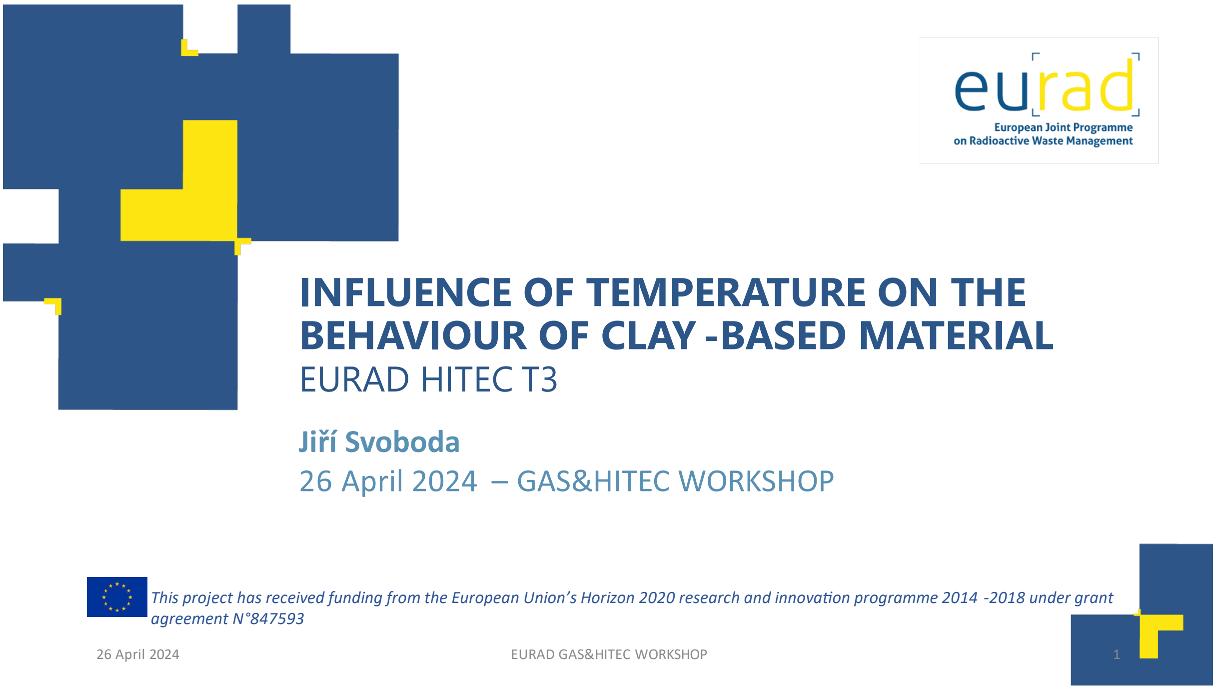
Afternoon session

How the results of the two WP (highlights in morning presentations) can be used by end-users to support repository design

- **Session 3 – Input to the repository design and the safety case** (13:30 – 16:00)
- Introduction by Séverine Levasseur & Markus Olin
- Key messages for treatment of high temperature by Olivier Leupin & Alexandros Papafotiou
- Key messages for treatment of gas transport by Jacques Wendling & Paul Marschall
- Final discussion (All)

Session 1: Temperature

1.1 Effect of high temperature on bentonite properties and processes



eurad
European Joint Programme on Radioactive Waste Management

INFLUENCE OF TEMPERATURE ON THE BEHAVIOUR OF CLAY -BASED MATERIAL

EURAD HITEC T3

Jiří Svoboda

26 April 2024 – GAS&HITEC WORKSHOP

This project has received funding from the European Union's Horizon 2020 research and innovation programme 2014 -2018 under grant agreement N°847593

26 April 2024 EURAD GAS&HITEC WORKSHOP 1

EURAD HITEC

- WP in EURAD
- 30 Organisations
- About 5 M€
- Leader VTT

ANDRA
BGE
BGR
BGS
BRGM
CEA
CIEMAT
UGrenoble
CTU
CU
EDF
ENRESA
EURIDICE
Ulorraine
GTK
UHelsinki
JYU
KIPT
LEI
NAGRA
POSIVA
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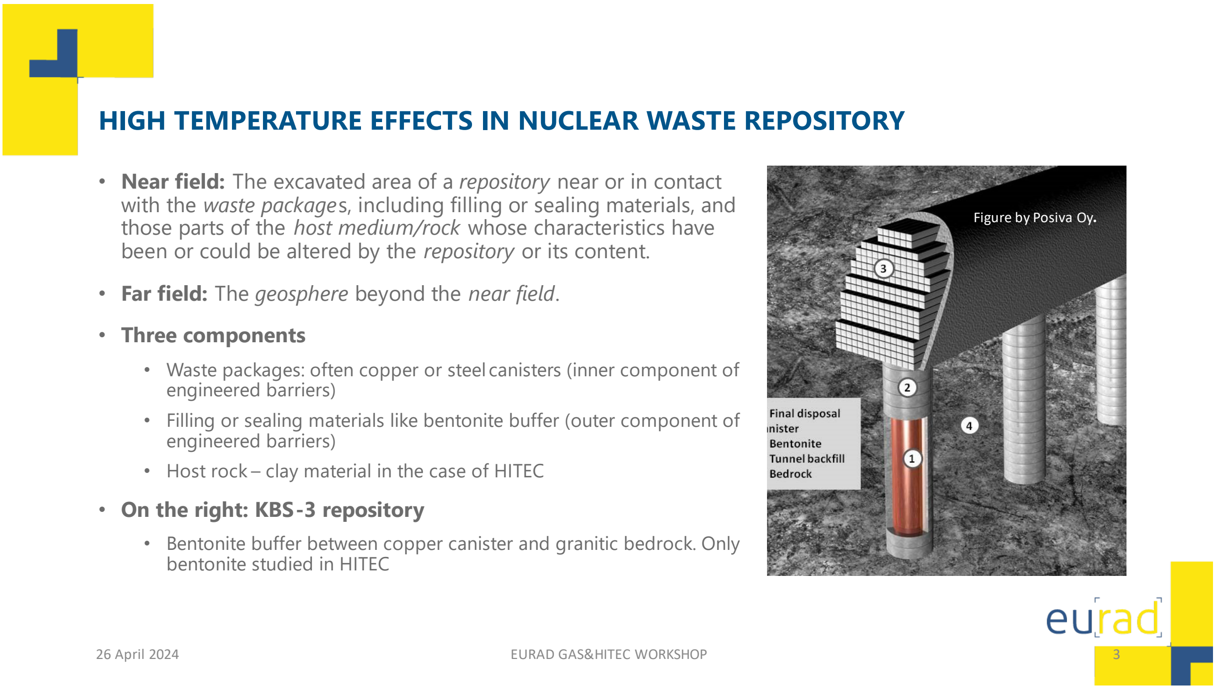
ÚJV
ULiège
UPC
VTT

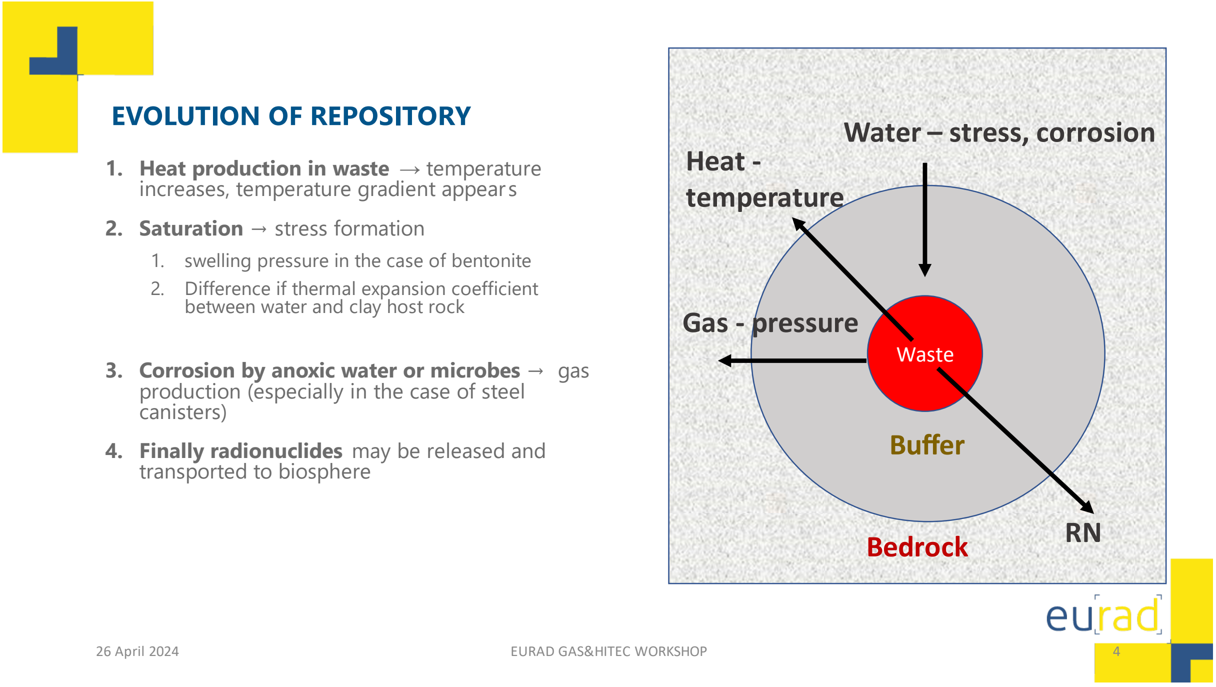


HIGH TEMPERATURE EFFECTS IN NUCLEAR WASTE REPOSITORY

- **Near field:** The excavated area of a *repository* near or in contact with the *waste packages*, including filling or sealing materials, and those parts of the *host medium/rock* whose characteristics have been or could be altered by the *repository* or its content.
- **Far field:** The *geosphere* beyond the *near field*.
- **Three components**
    - Waste packages: often copper or steel canisters (inner component of engineered barriers)
    - Filling or sealing materials like bentonite buffer (outer component of engineered barriers)
    - Host rock – clay material in the case of HITEC
- **On the right: KBS-3 repository**
    - Bentonite buffer between copper canister and granitic bedrock. Only bentonite studied in HITEC

Figure by Posiva Oy.

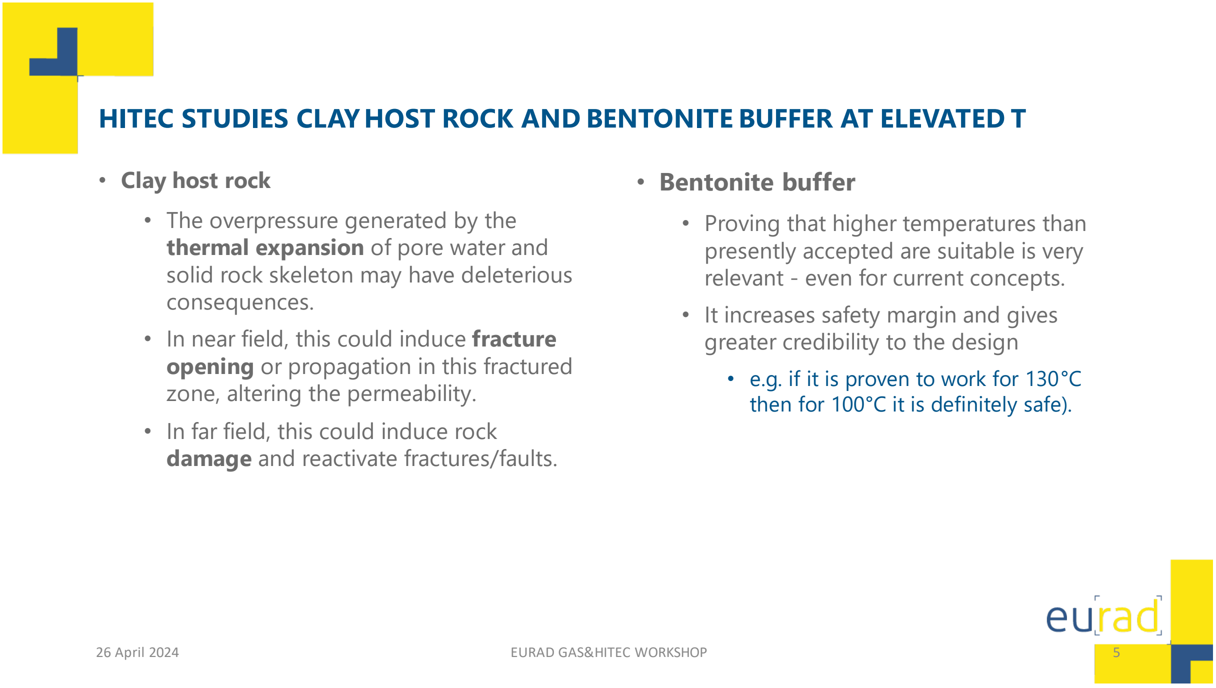
26 April 2024 EURAD GAS&HITEC WORKSHOP 3



EVOLUTION OF REPOSITORY

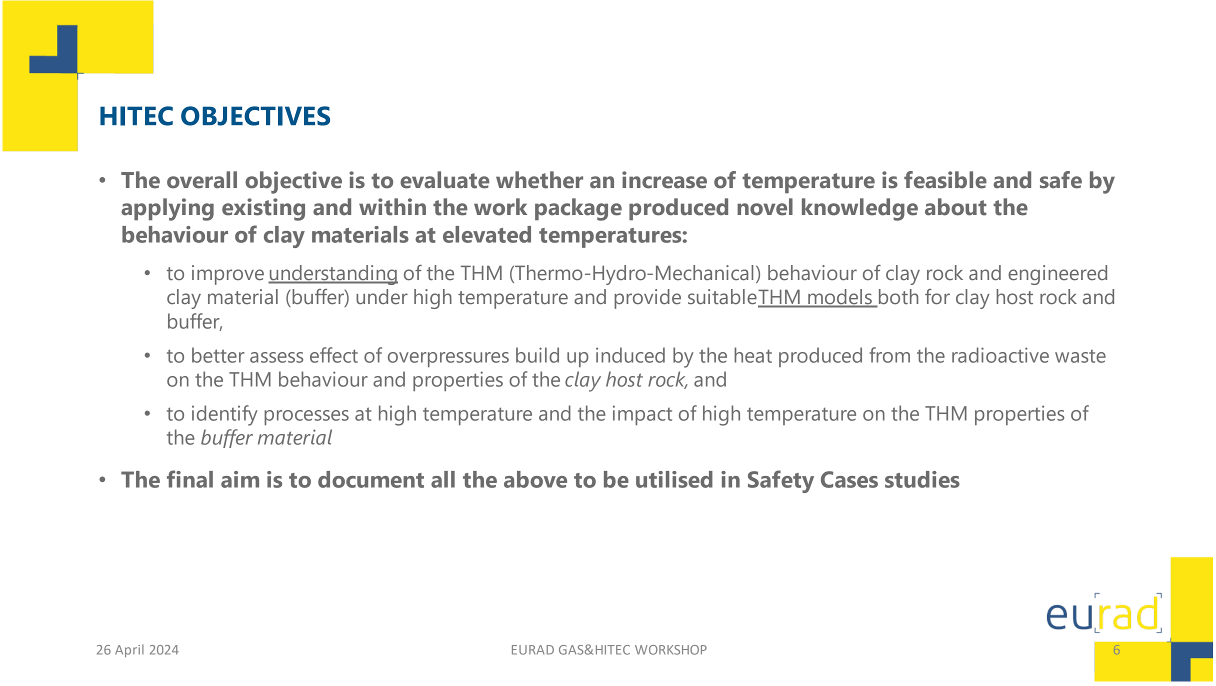
1. **Heat production in waste** → temperature increases, temperature gradient appears
2. **Saturation** → stress formation
    1. swelling pressure in the case of bentonite
    2. Difference if thermal expansion coefficient between water and clay host rock
3. **Corrosion by anoxic water or microbes** → gas production (especially in the case of steel canisters)
4. **Finally radionuclides** may be released and transported to biosphere

26 April 2024 EURAD GAS&HITEC WORKSHOP 4



HITEC STUDIES CLAY HOST ROCK AND BENTONITE BUFFER AT ELEVATED T

- **Clay host rock**
  - The overpressure generated by the **thermal expansion** of pore water and solid rock skeleton may have deleterious consequences.
  - In near field, 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.
- **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 definitely safe).

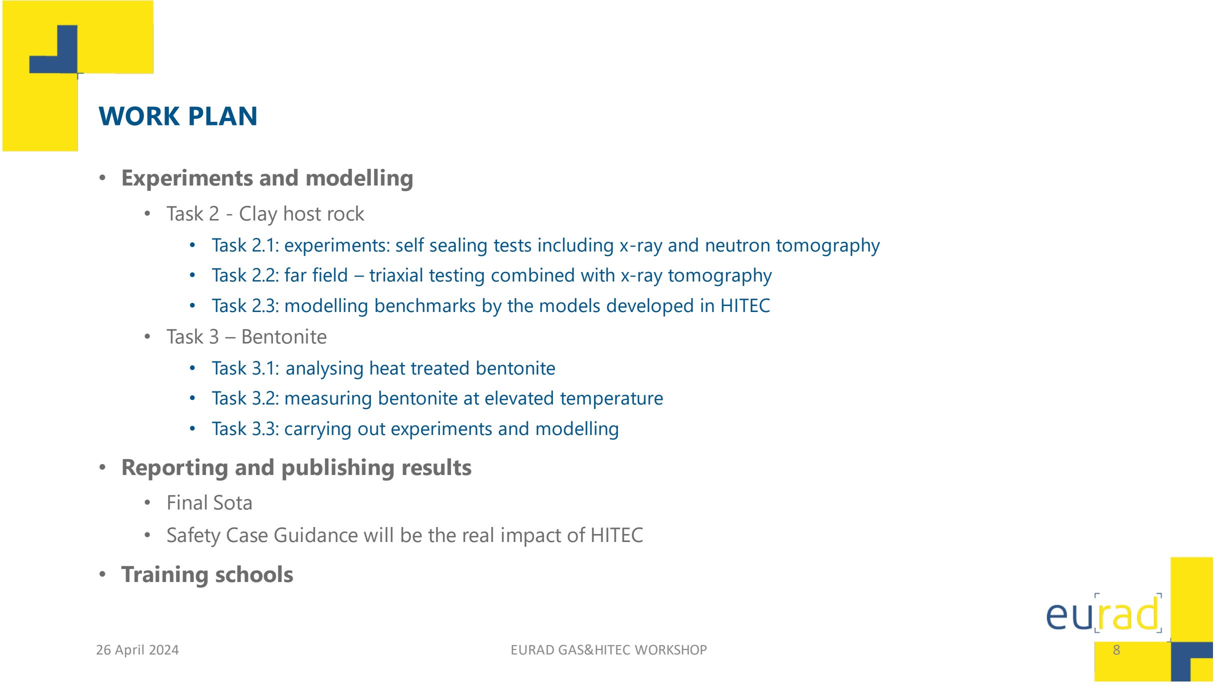


HITEC OBJECTIVES

- **The overall objective is to evaluate whether an increase of temperature is feasible and safe by applying existing and within the work package produced novel knowledge about the behaviour of clay materials at elevated temperatures:**
  - to improve understanding of the THM (Thermo-Hydro-Mechanical) behaviour of clay rock and engineered clay material (buffer) under high temperature and provide suitable THM models both for clay host rock and buffer,
  - to better assess effect of overpressures build up induced by the heat produced from the radioactive waste on the THM behaviour and properties of the *clay host rock,* and
  - to identify processes at high temperature and the impact of high temperature on the THM properties of the *buffer material*
- **The final aim is to document all the above to be utilised in Safety Cases studies**

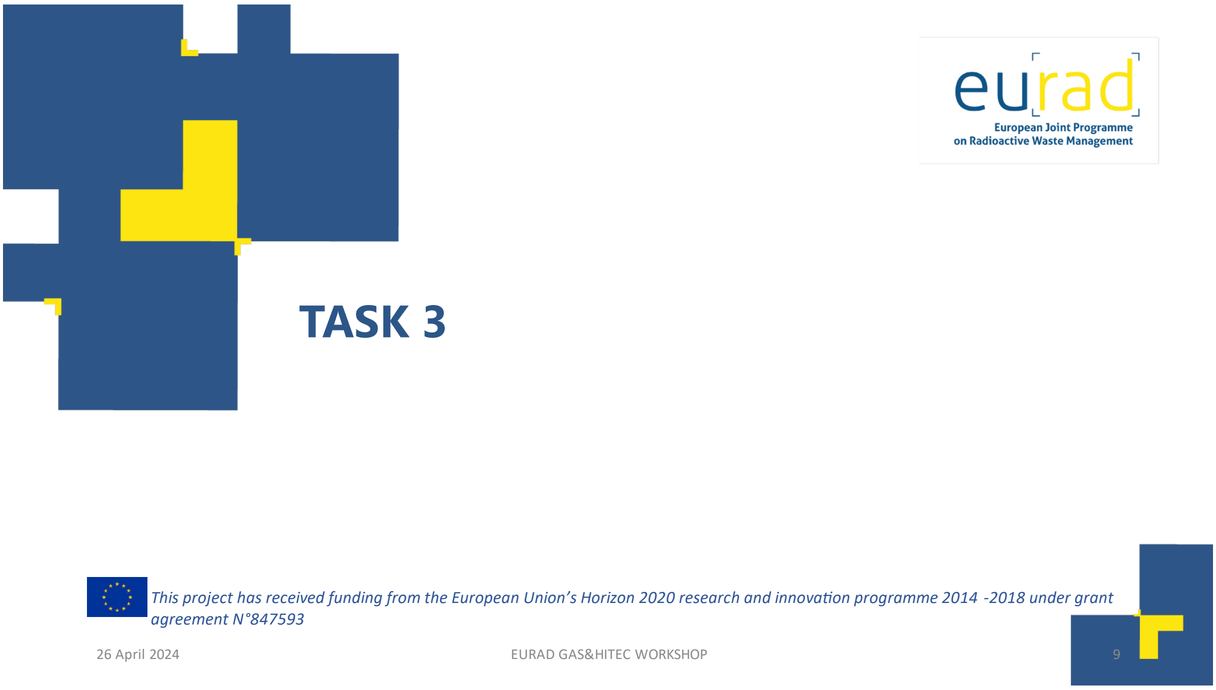
METHODS AND EQUIPMENTS

- **Experiments**
  - Mechanical experiments in different setups
  - Swelling and permeability tests
  - Mostly lab scale at elevated temperatures
- **Measurements**
  - Stress, deformation, ..hydraulic conductivity, temperature
  - Both X-ray and neutron tomography
- **Modelling**
  - Models for mechanical behaviour both for clay host rock and bentonite
  - Differences
    - Fracture formation in clay host rock
    - Significant deformation of bentonite (swelling)



WORK PLAN

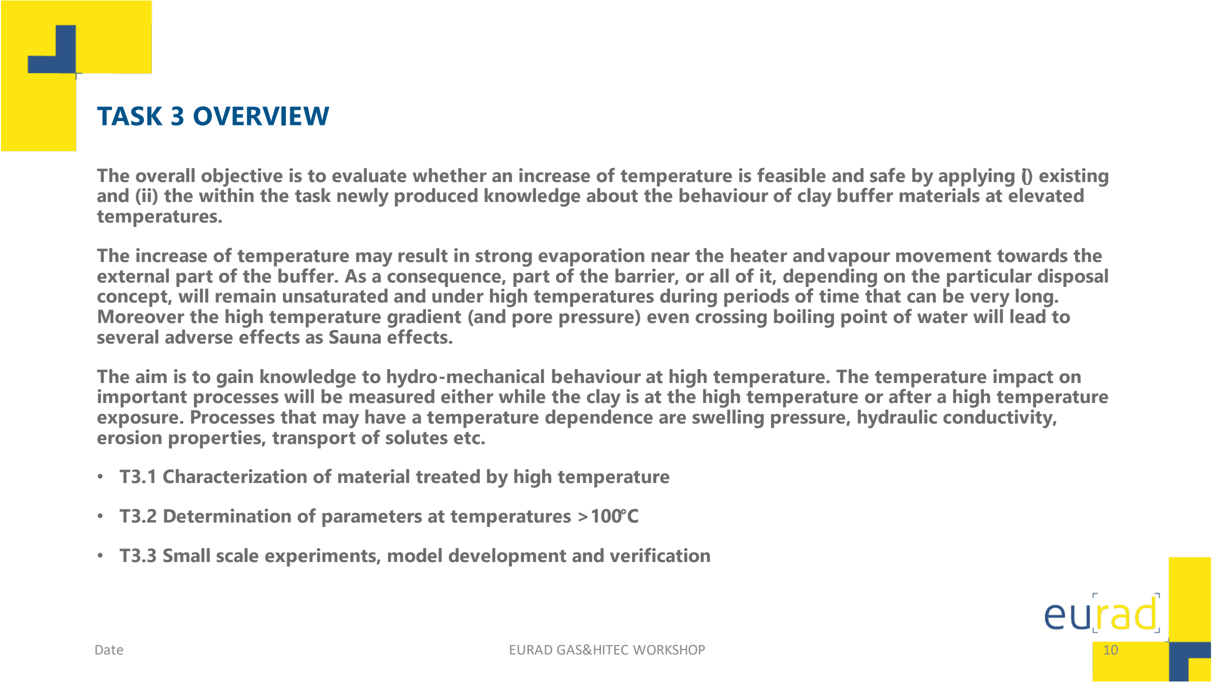
- **Experiments and modelling**
  - Task 2 - Clay host rock
    - Task 2.1: experiments: self sealing tests including x-ray and neutron tomography
    - Task 2.2: far field – triaxial testing combined with x-ray tomography
    - Task 2.3: modelling benchmarks by the models developed in HITEC
  - Task 3 – Bentonite
    - Task 3.1: analysing heat treated bentonite
    - Task 3.2: measuring bentonite at elevated temperature
    - Task 3.3: carrying out experiments and modelling
- **Reporting and publishing results**
  - Final Sota
  - Safety Case Guidance will be the real impact of HITEC
- **Training schools**



TASK 3

This project has received funding from the European Union’s Horizon 2020 research and innovation programme 2014 -2018 under grant agreement N°847593

26 April 2024 EURAD GAS&HITEC WORKSHOP 9



TASK 3 OVERVIEW

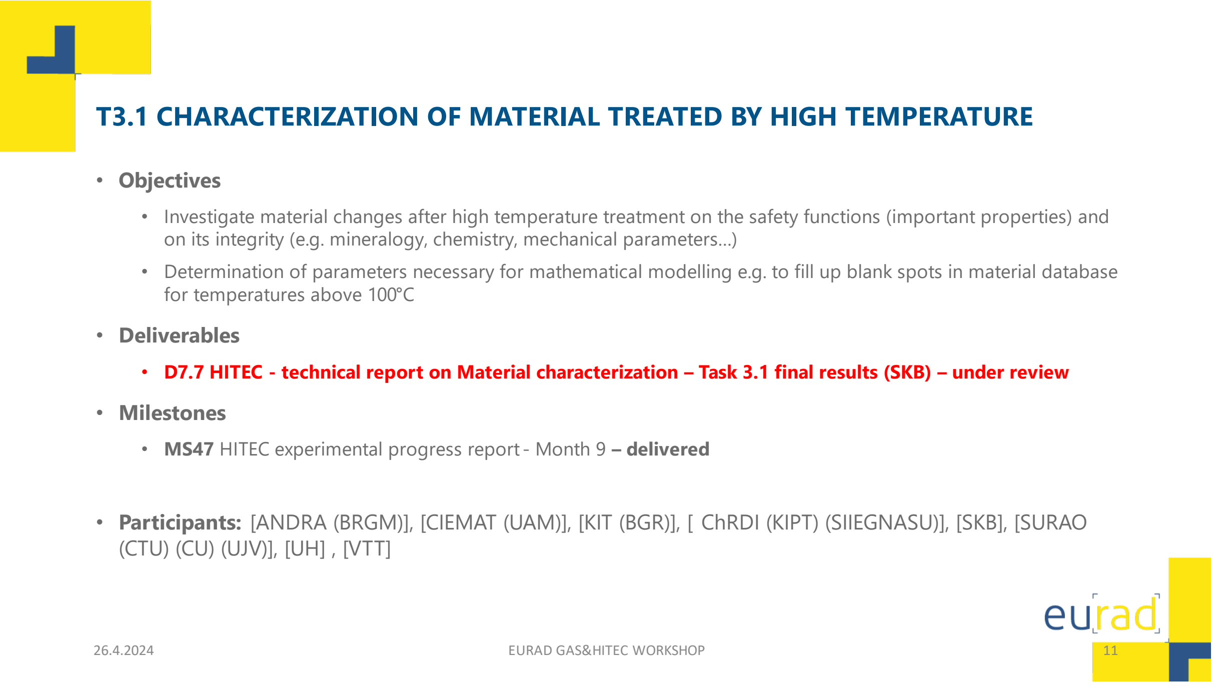
The overall objective is to evaluate whether an increase of temperature is feasible and safe by applying (i) existing and (ii) the within the task newly produced knowledge about the behaviour of clay buffer materials at elevated temperatures.

The increase of temperature may result in strong evaporation near the heater and vapour movement towards the external part of the buffer. As a consequence, part of the barrier, or all of it, depending on the particular disposal concept, will remain unsaturated and under high temperatures during periods of time that can be very long. Moreover the high temperature gradient (and pore pressure) even crossing boiling point of water will lead to several adverse effects as Sauna effects.

The aim is to gain knowledge to hydro-mechanical behaviour at high temperature. The temperature impact on important processes will be measured either while the clay is at the high temperature or after a high temperature exposure. Processes that may have a temperature dependence are swelling pressure, hydraulic conductivity, erosion properties, transport of solutes etc.

- **T3.1 Characterization of material treated by high temperature**
- **T3.2 Determination of parameters at temperatures > 100°C**
- **T3.3 Small scale experiments, model development and verification**

Date EURAD GAS&HITEC WORKSHOP 10

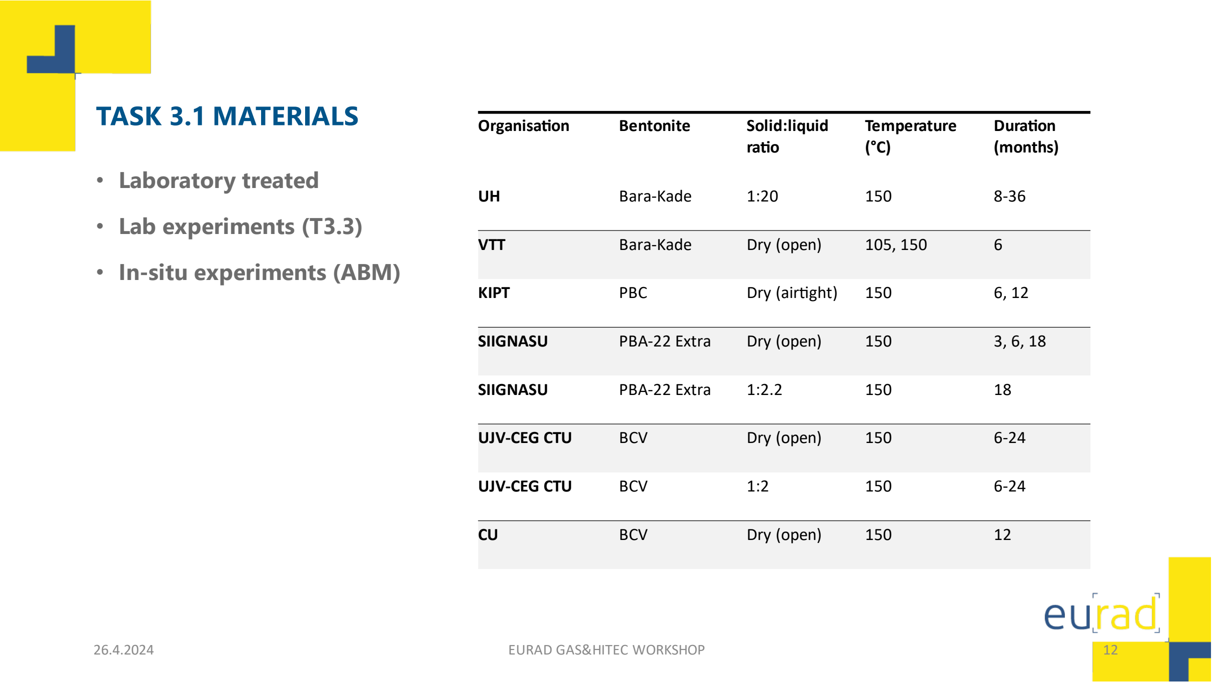


T3.1 CHARACTERIZATION OF MATERIAL TREATED BY HIGH TEMPERATURE

- **Objectives**
  - 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
- **Deliverables**
  - **D7.7 HITEC - technical report on Material characterization – Task 3.1 final results (SKB) – under review**
- **Milestones**
  - **MS47** HITEC experimental progress report - Month 9 **– delivered**

- **Participants:** [ANDRA (BRGM)], [CIEMAT (UAM)], [KIT (BGR)], [ChRDI (KIPT) (SIIEGNASU)], [SKB], [SURAO (CTU) (CU) (UJV)], [UH] , [VTT]

26.4.2024 EURAD GAS&HITEC WORKSHOP 11



TASK 3.1 MATERIALS

- **Laboratory treated**
- **Lab experiments (T3.3)**
- **In-situ experiments (ABM)**

Organisation	Bentonite	Solid:liquid ratio	Temperature (°C)	Duration (months)
UH	Bara-Kade	1:20	150	8-36
VTT	Bara-Kade	Dry (open)	105, 150	6
KIPT	PBC	Dry (airtight)	150	6, 12
SIIGNASU	PBA-22 Extra	Dry (open)	150	3, 6, 18
SIIGNASU	PBA-22 Extra	1:2.2	150	18
UJV-CEG CTU	BCV	Dry (open)	150	6-24
UJV-CEG CTU	BCV	1:2	150	6-24
CU	BCV	Dry (open)	150	12

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TASK 3.1 WHAT HAS BEEN STUDIED?

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

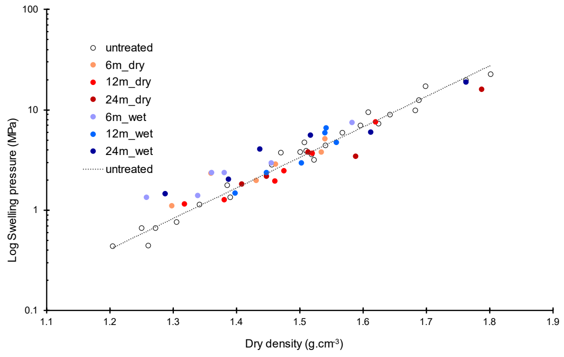
TASK 3.1 RESULTS AND CONCLUSION

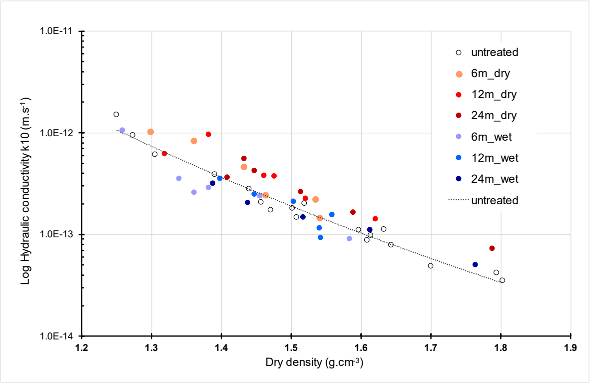
- No general significant transformation of montmorillonite was observed in the experiments.
- In several cases the CEC of the bentonite was affected by the heating.
- There are indications that dry heating of bentonite seems to affect the clay in other ways, than heating of water saturated bentonite.
- 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).

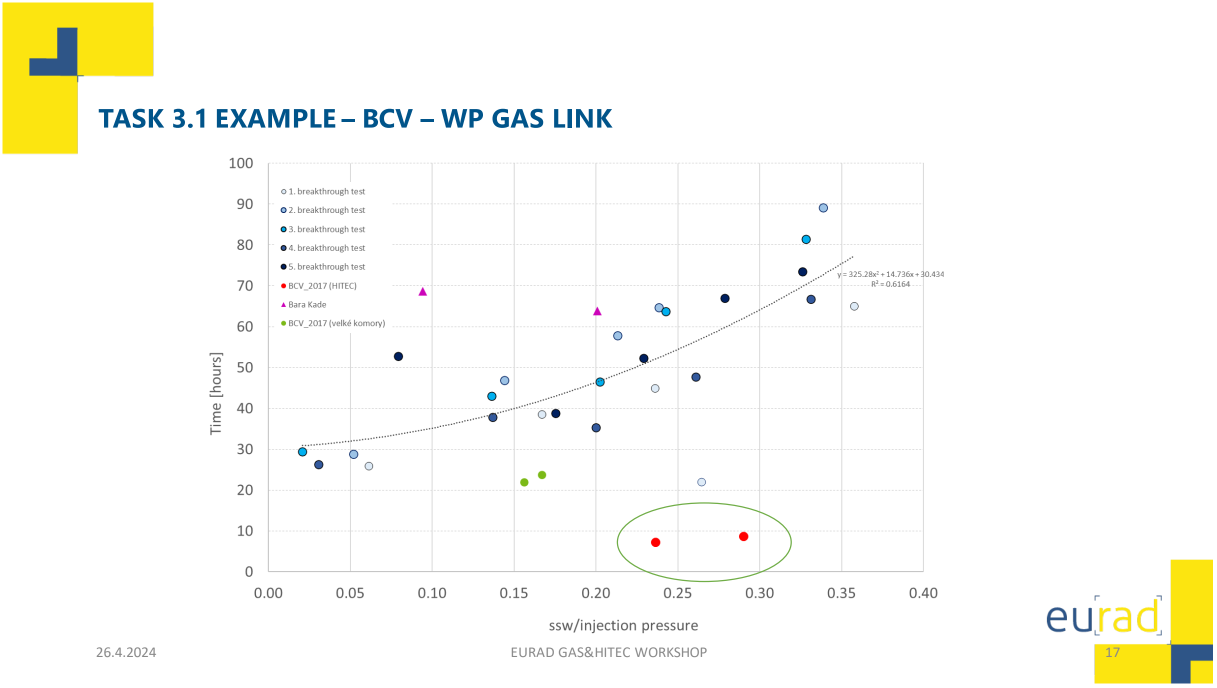
TASK 3.1 RESULTS AND CONCLUSION

- **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 actually 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.**

TASK 3.1 EXAMPLE – BCV SWELLING PRESSURE AND PERMEABILITY







TASK 3.1 EXAMPLE – BCV – WP GAS LINK

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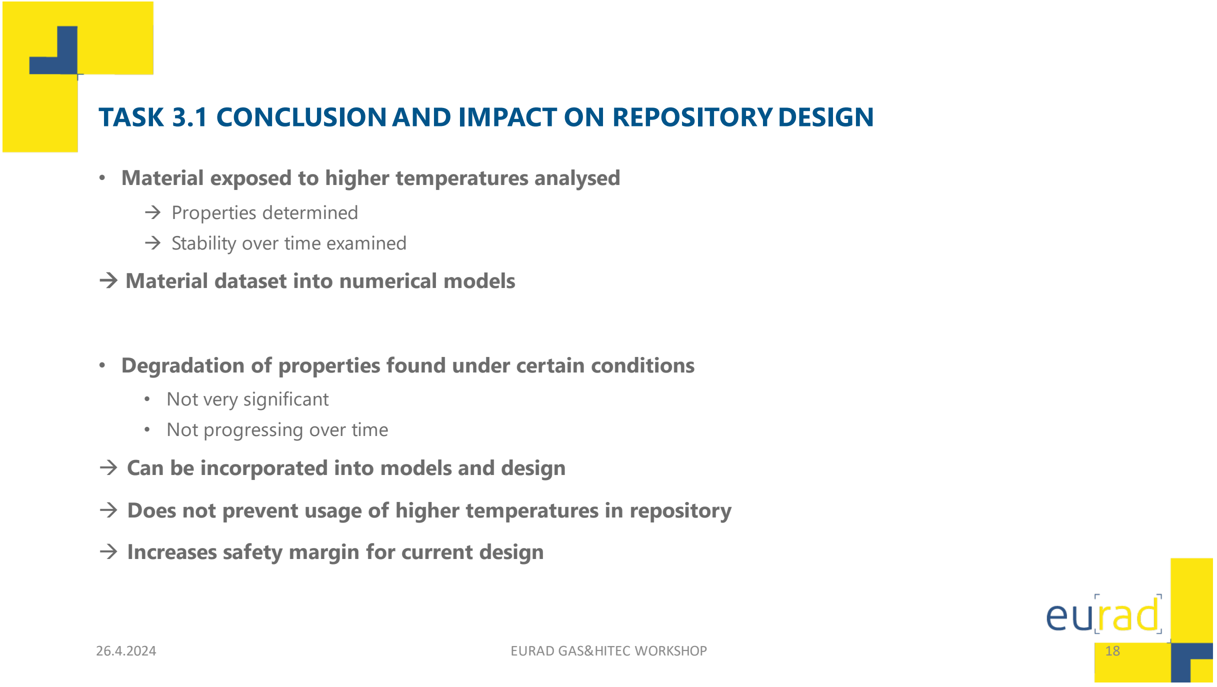

TASK 3.1 CONCLUSION AND IMPACT ON REPOSITORY DESIGN

- **Material exposed to higher temperatures analysed**
  - → Properties determined
  - → Stability over time examined

→ Material dataset into numerical models

- **Degradation of properties found under certain conditions**
  - Not very significant
  - Not progressing over time

→ Can be incorporated into models and design

→ Does not prevent usage of higher temperatures in repository

→ Increases safety margin for current design

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T3.2 DETERMINATION OF PARAMETERS AT TEMPERATURES >100°C

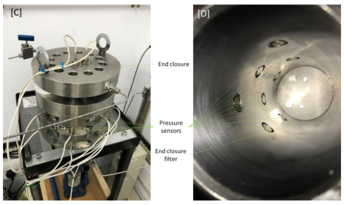
- **Objectives**
  - Investigate processes and material properties at high temperature
  - Determination of parameters necessary for mathematical modelling (input into Subtask 3.3)
- **Deliverables**
  - **D7.8 HITEC technical report on test at high temperature– Task 3.2 final results (UKRI-BGS) – under review**
- **Milestones**
  - **MS47** HITEC experimental progress report - Month 9 **– delivered**
- **Participants:** [Andra (BRGM)], [UKRI-BGS], [ChRDI (KIPT)], [CIEMAT], [RWM], [SURAO (CTU) (CU)], [UH (GTK) (JYU)], [VTT]

TASK 3.2 MATERIALS TESTED

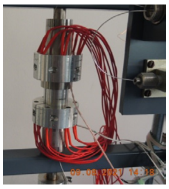
- **MX-80**
- **Imersys Ca bentonite**
- **Kunipia G**
- **FEBEX**
- **BARA-KADE**
- **BCV**
- **PBC**

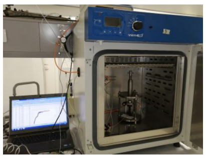
TASK 3.2 WHAT HAS BEEN STUDIED?

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

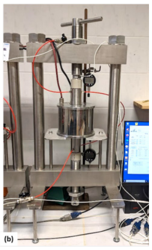


[BGS © UKRI]

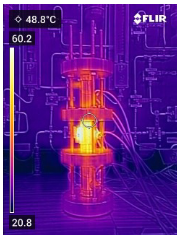




[BRGM]



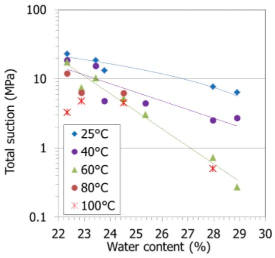
[CU]



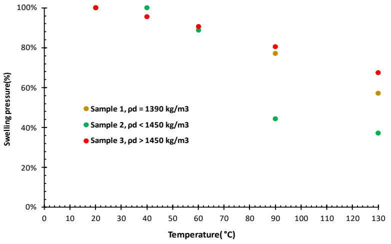
[CTU]

TASK 3.2 HIGHLIGHTS AND CONCLUSION

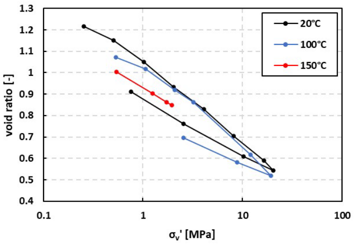
- WRCs – sharper decrease observed at higher temperatures (particularly above 60°C)
- Swelling pressure - decrease with higher temperatures (above 50°C) – needs more characterisation
- Permeability less sensitive to high temperature



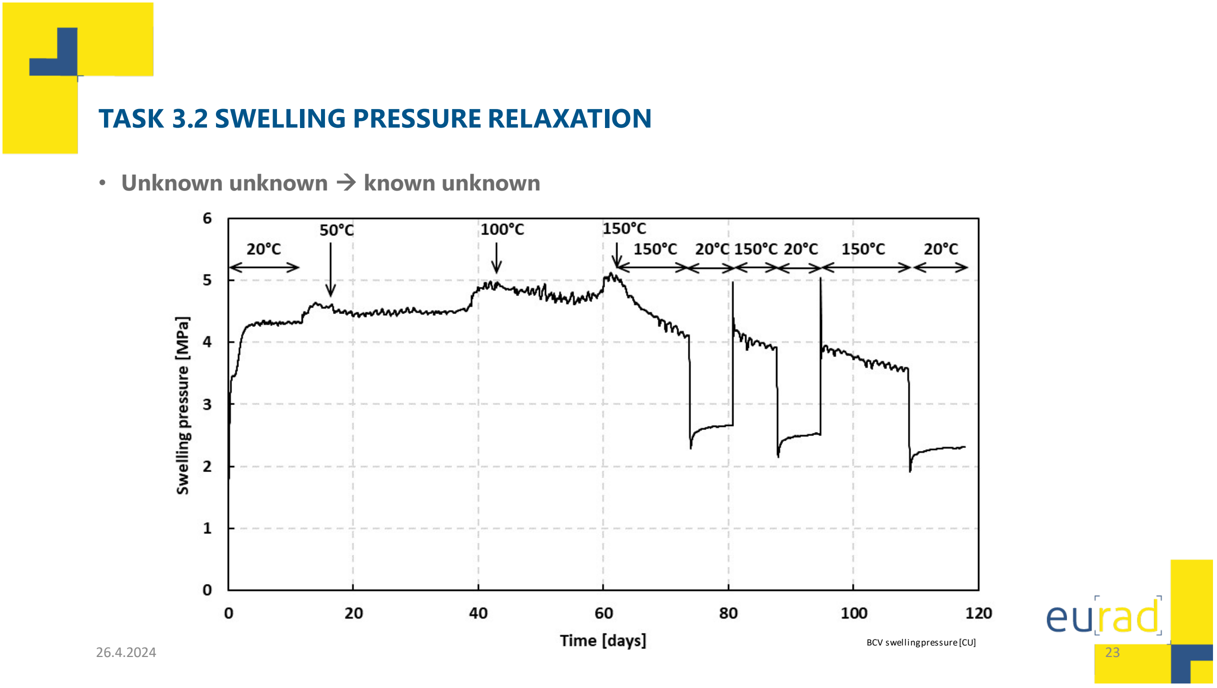
FEBEX 1.6 g/cm³ [CIEMAT]



Swelling pressure decrease [CTU]



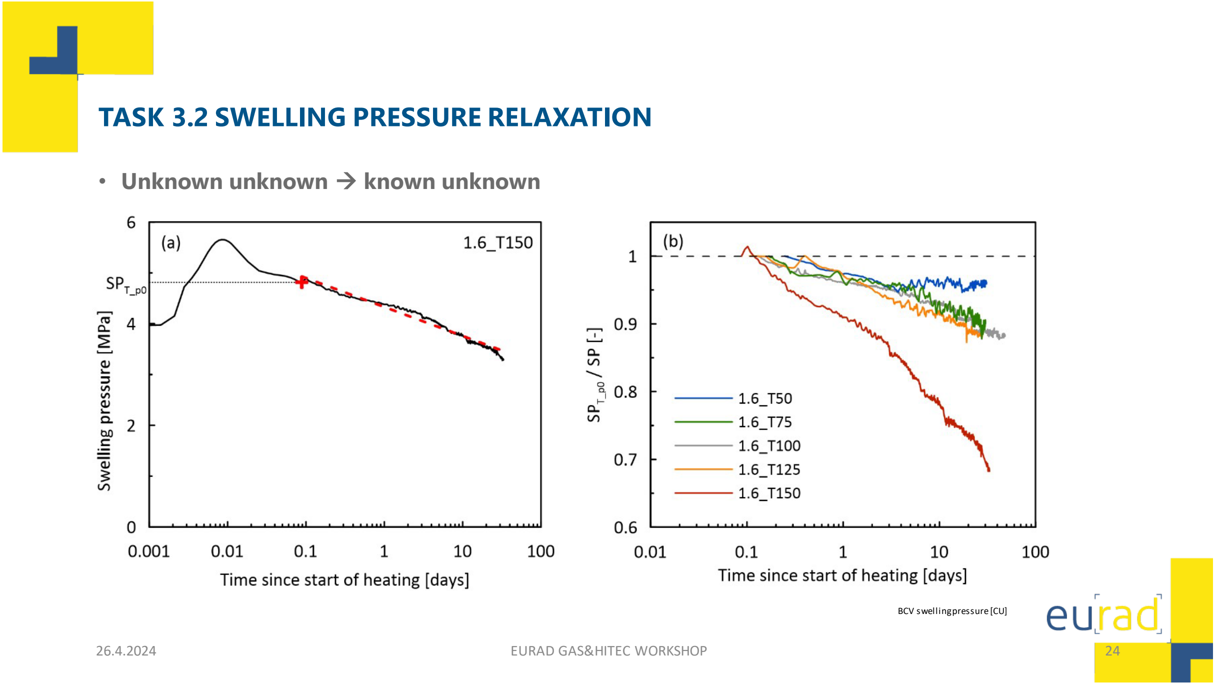
BCV compression curves [CU]



TASK 3.2 SWELLING PRESSURE RELAXATION

- **Unknown unknown → known unknown**

BCV swellingpressure [CU]



TASK 3.2 SWELLING PRESSURE RELAXATION

- **Unknown unknown → known unknown**

BCV swellingpressure [CU]

TASK 3.2 HIGHLIGHTS AND CONCLUSION

Jan Najser, David Mašín,

An experimental study on thermal relaxation of BCV bentonite,

Applied Clay Science, Volume 254, 2024,107374, ISSN 0169-1317

- https://doi.org/10.1016/j.clay.2024.107374

TASK 3.2 CONCLUSION AND IMPACT ON REPOSITORY DESIGN

- **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**

→**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 phenome all included (minor)**

T3.3 SMALL SCALE EXPERIMENTS, MODEL DEVELOPMENT AND VERIFICATION

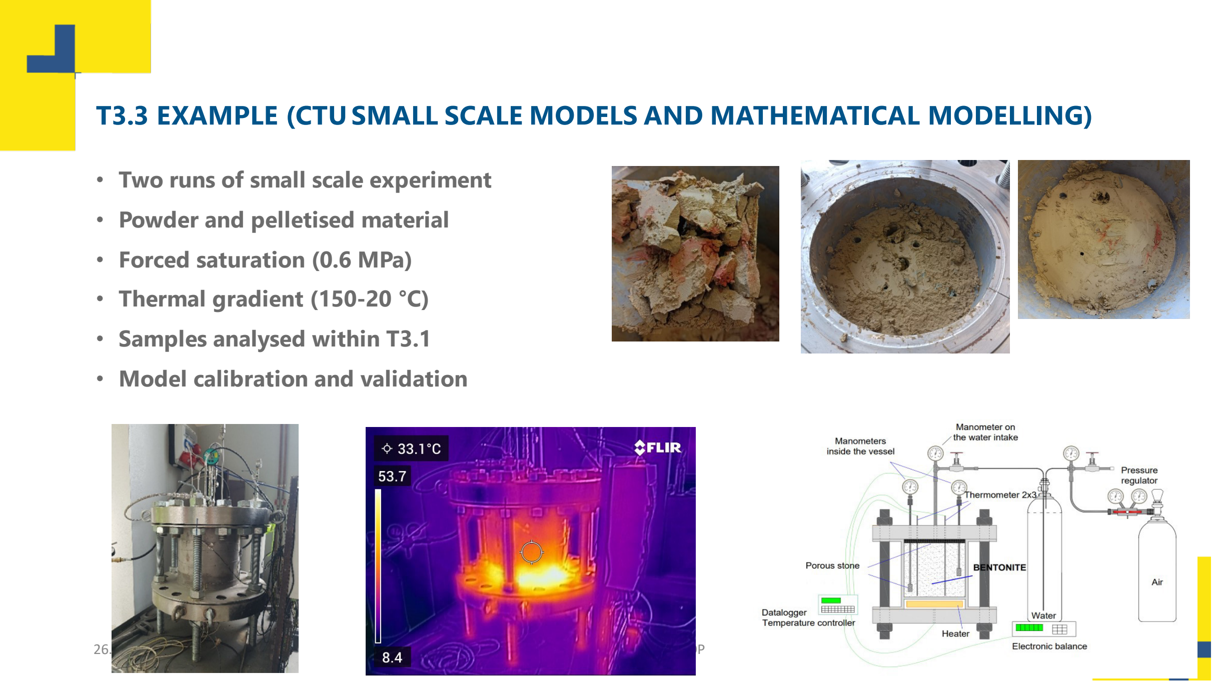
- **Objectives**
  - Understanding of processes at larger scale
  - Development and validation of mathematical models (at concept/element level)
  - Benchmark of available and developed codes to assess their suitability for high temperatures

- **Deliverables**
  - **D7.9 HITEC - Experimental works (small and midscale laboratory experiments)– final report (Results of the experimental works of T3.3) (CIEMAT)**
  - **D7.10 HITEC - Modelling – final report (Results of all modelling task carried in T3.3 in cooperation with DONUT (CIEMAT)**

T3.3 SMALL SCALE EXPERIMENTS, MODEL DEVELOPMENT AND VERIFICATION

- **Milestones**
  - **MS47** HITEC experimental progress report - Month 9 **– delivered**
  - **MS63** HITEC Task 3.3 - Mathematical models – description of models and plan for improvements (Description of conceptual models and tools, plan for the models improvement)- Month 12 **– delivered**
  - **MS130** HITEC Task 3.3 -Modelling benchmarks – description (Description of calibration case, verification cases and benchmarks selected for T3.3 in cooperation with DONUT) - Month 24 **– delivered**

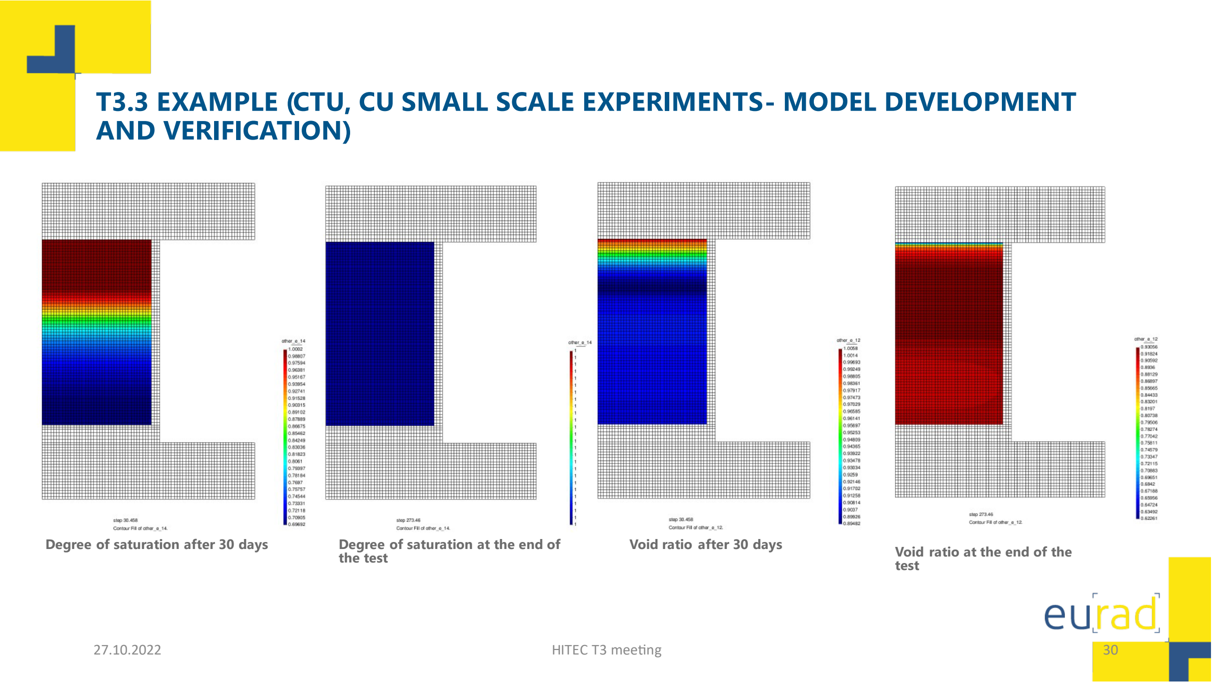
- **Participants: [CIEMAT (UPC)], [POSIVA], [SÚRAO (CTU) (CU)], [VTT]**



T3.3 EXAMPLE (CTU SMALL SCALE MODELS AND MATHEMATICAL MODELLING)

- Two runs of small scale experiment
- Powder and pelletised material
- Forced saturation (0.6 MPa)
- Thermal gradient (150-20 °C)
- Samples analysed within T3.1
- Model calibration and validation

26.



T3.3 EXAMPLE (CTU, CU SMALL SCALE EXPERIMENTS - MODEL DEVELOPMENT AND VERIFICATION)

Degree of saturation after 30 days

Degree of saturation at the end of the test

Void ratio after 30 days

Void ratio at the end of the test

27.10.2022 HITEC T3 meeting 30

TASK 3.3 HIGHLIGHTS AND CONCLUSION

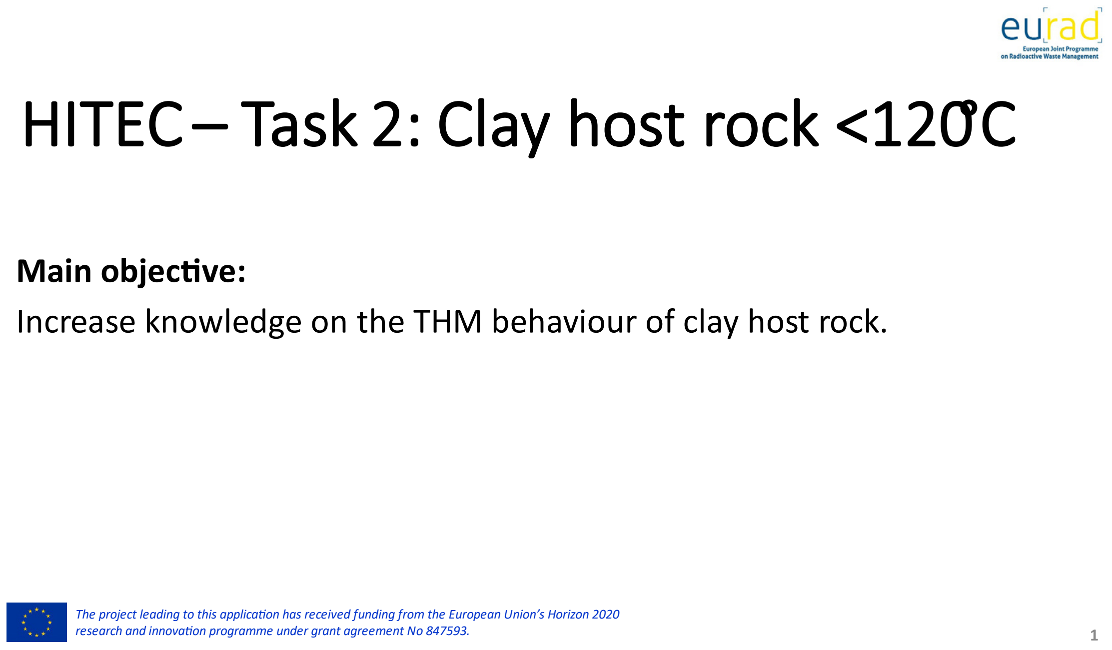
- **Experiments**
  - Data
    - → Model development and validation
  - Samples
    - → Analysed within T3.1
    - → Results coherent with results from lab tests
- **Models**
  - Calibration data from T3.1 and T3.2 incorporated
  - Models improved to represent behaviour above 100 C. However, some effect of temperature still need to incorporated
  - Models validated/benchmarked against experiments
  - Joint benchmark with DONUT

T3 CONCLUSION - HIGHLIGHTS BENTONITE BUFFER

- **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)**

1.2 Measuring clayey host rock behavior at high temperatures



HITEC – Task 2: Clay host rock <120°C

Main objective:

Increase knowledge on the THM behaviour of clay host rock.

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

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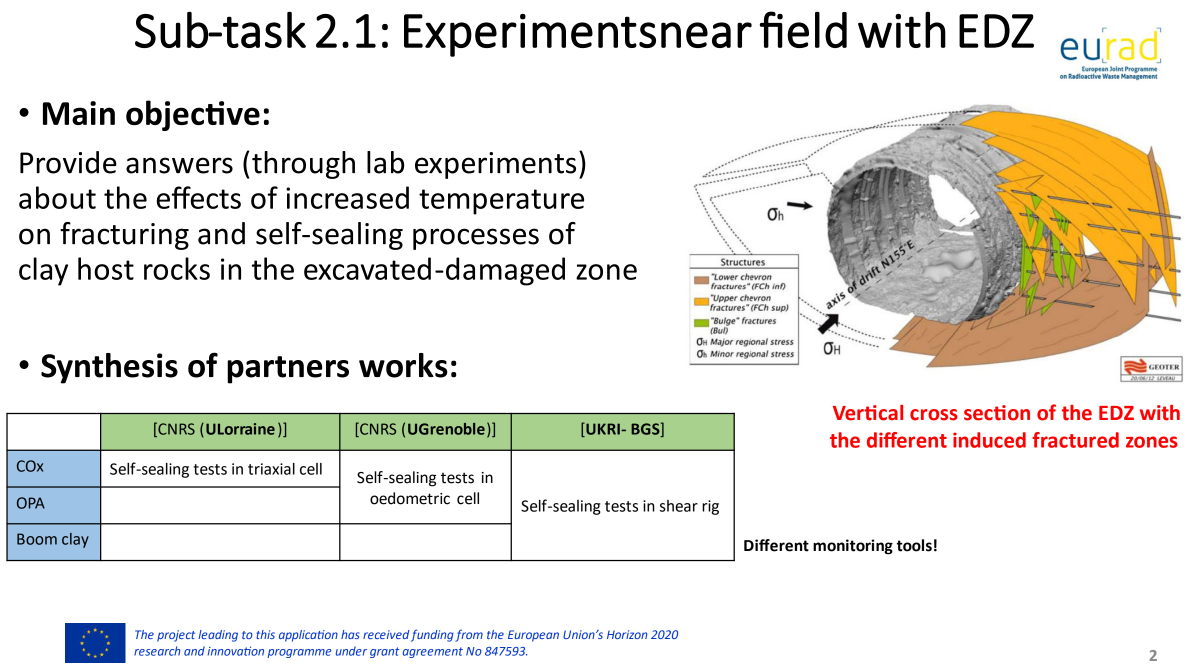

Sub-task 2.1: Experiments near field with EDZ

- **Main objective:**

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

- **Synthesis of partners works:**

	[CNRS (**ULorraine**)]	[CNRS (**UGrenoble**)]	[**UKRI- BGS**]
COx	Self-sealing tests in triaxial cell	Self-sealing tests in oedometric cell	Self-sealing tests in shear rig
OPA			
Boom clay			

Vertical cross section of the EDZ with the different induced fractured zones

Different monitoring tools!

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

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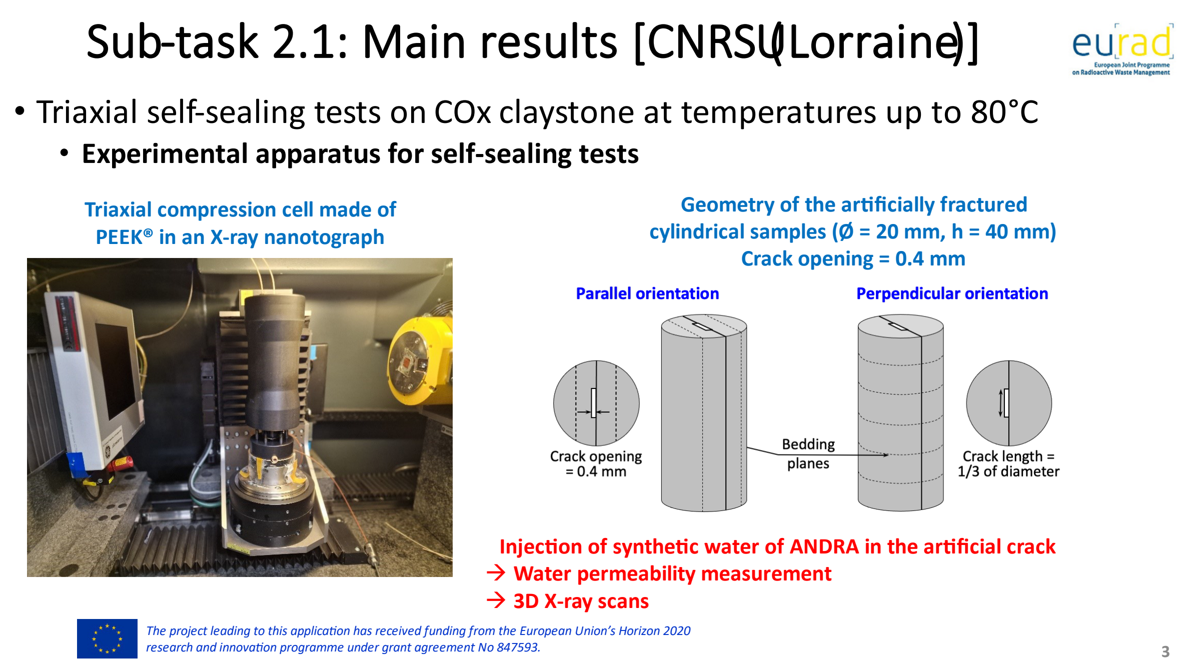

Sub-task 2.1: Main results [CNRSU(Lorraine)]

- Triaxial self-sealing tests on COx claystone at temperatures up to 80°C
  - **Experimental apparatus for self-sealing tests**

Triaxial compression cell made of PEEK® in an X-ray nanotograph

Geometry of the artificially fractured cylindrical samples (Ø = 20 mm, h = 40 mm)
Crack opening = 0.4 mm

Injection of synthetic water of ANDRA in the artificial crack
→ Water permeability measurement
→ 3D X-ray scans

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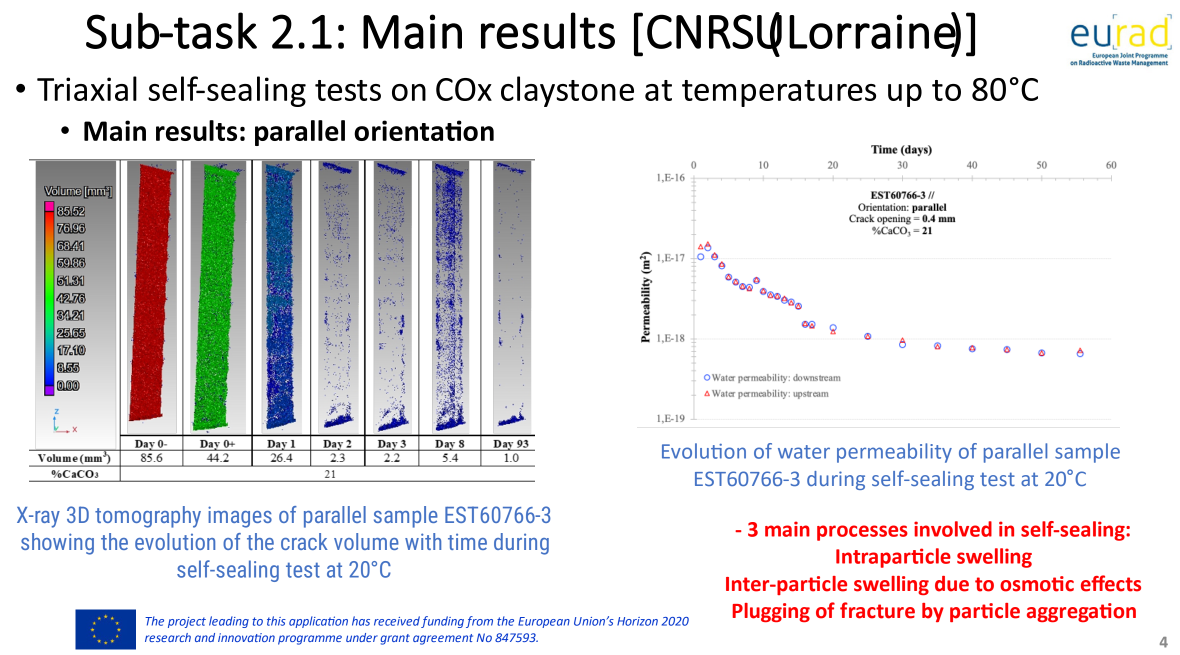

Sub-task 2.1: Main results [CNRSU(Lorraine)]

- Triaxial self-sealing tests on COx claystone at temperatures up to 80°C
  - **Main results: parallel orientation**

	Day 0-	Day 0+	Day 1	Day 2	Day 3	Day 8	Day 93
Volume (mm³)	85.6	44.2	26.4	2.3	2.2	5.4	1.0
%CaCO₃	21						

X-ray 3D tomography images of parallel sample EST60766-3 showing the evolution of the crack volume with time during self-sealing test at 20°C

Evolution of water permeability of parallel sample EST60766-3 during self-sealing test at 20°C

- 3 main processes involved in self-sealing:
Intraparticle swelling
Inter-particle swelling due to osmotic effects
Plugging of fracture by particle aggregation

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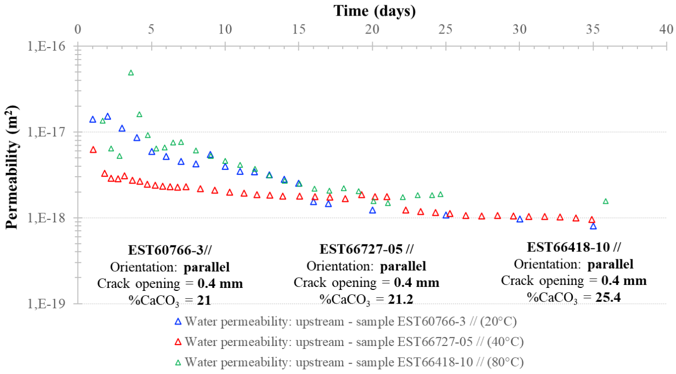
Sub-task 2.1: Main results [CNRSU(Lorraine)]

- Triaxial self-sealing tests on COx claystone at temperatures up to 80°C
  - **Main results: parallel orientation**



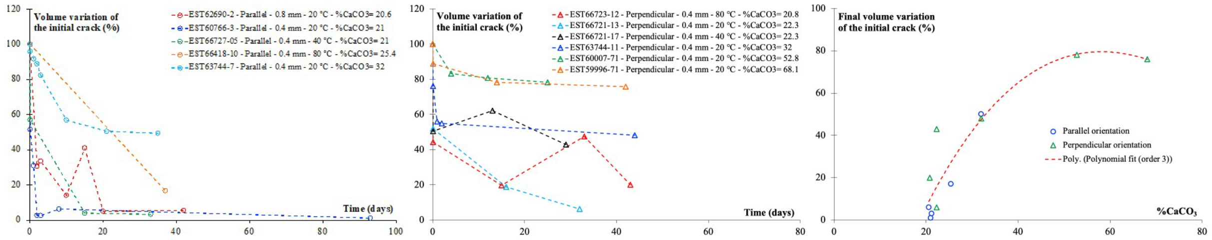
Evolution of water permeability of **parallel** samples: Self-sealing tests at 20˚C, 40 ˚C and 80˚C

No significant impact of temperature on the self-sealing process

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

Sub-task 2.1: Main results [CNRSU(Lorraine)]

- Triaxial self-sealing tests on COx claystone at temperatures up to 80°C
  - **Main results: parallel and perpendicular orientation**



Volume variation percentage of the initial crack obtained from X-ray tomography 3D images during self-sealing tests with water

Self-sealing process depends strongly on the calcite content
→ Max. calcite content for self-sealing: ~40%

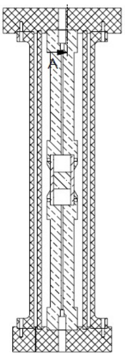
The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

Sub-task 2.1: Main results [CNRS (Grenoble)]

- Self-sealing tests on COx claystone at temperatures up to 90°C
  - **Experimental apparatus for self-sealing tests**

Motivations

- Experimental characterization of the synthetic axial crack sealing using bimodal x-ray and neutron CT (ILL)
- Quantification of kinematic (swelling) and water content change process during sealing
- Effects of temperature and bedding orientation



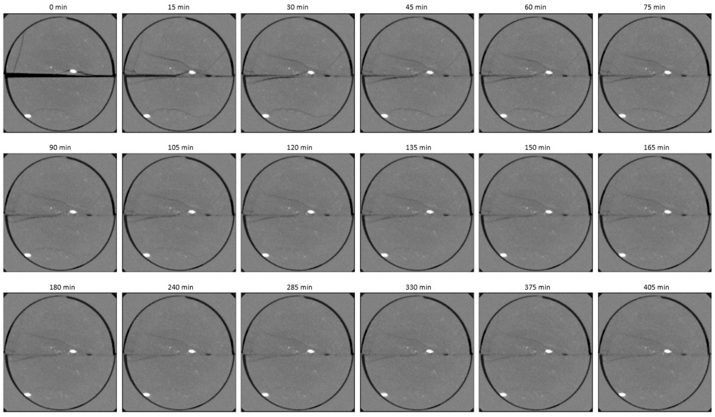
Testing cell for self-sealing tests

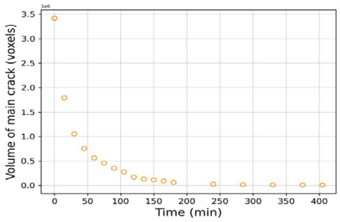
The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

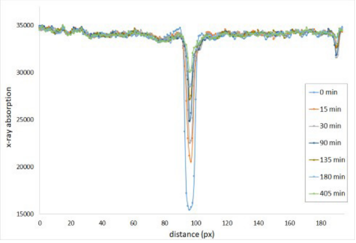
Sub-task 2.1: Main results [CNRS (Grenoble)]

- Self-sealing tests on COx claystone at temperatures up to 90°C
  - **Main results: parallel orientation, 90 °C**

X-ray CT







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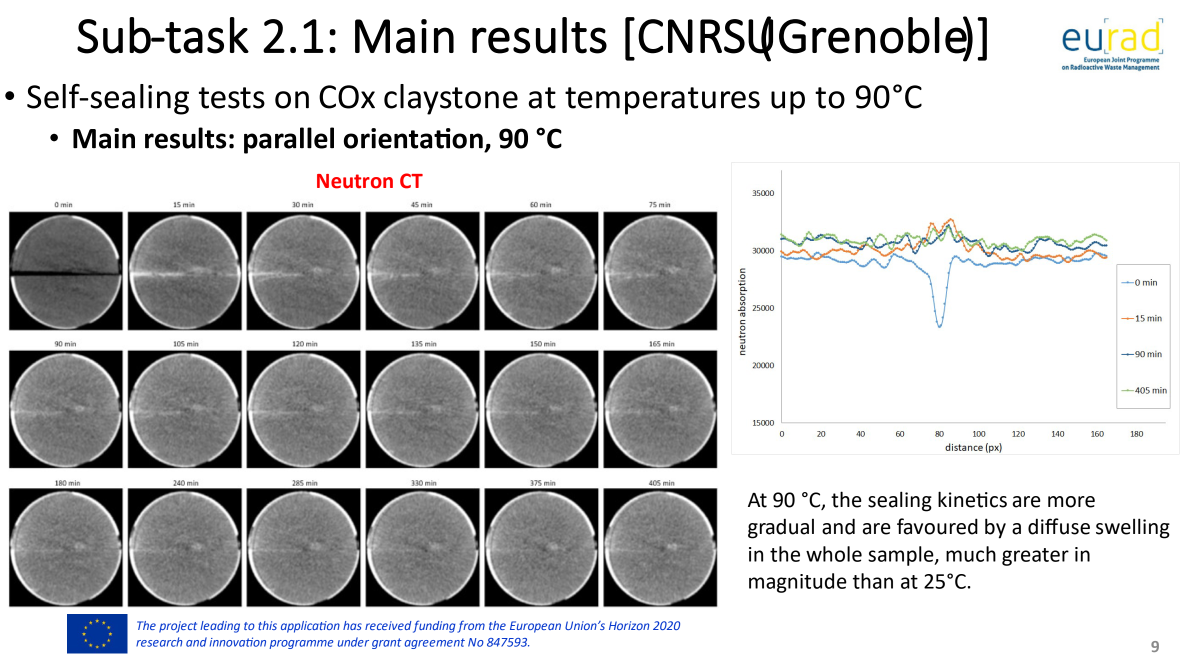

Sub-task 2.1: Main results [CNRS (Grenoble)]

- Self-sealing tests on COx claystone at temperatures up to 90°C
  - **Main results: parallel orientation, 90 °C**

At 90 °C, the sealing kinetics are more gradual and are favoured by a diffuse swelling in the whole sample, much greater in magnitude than at 25°C.

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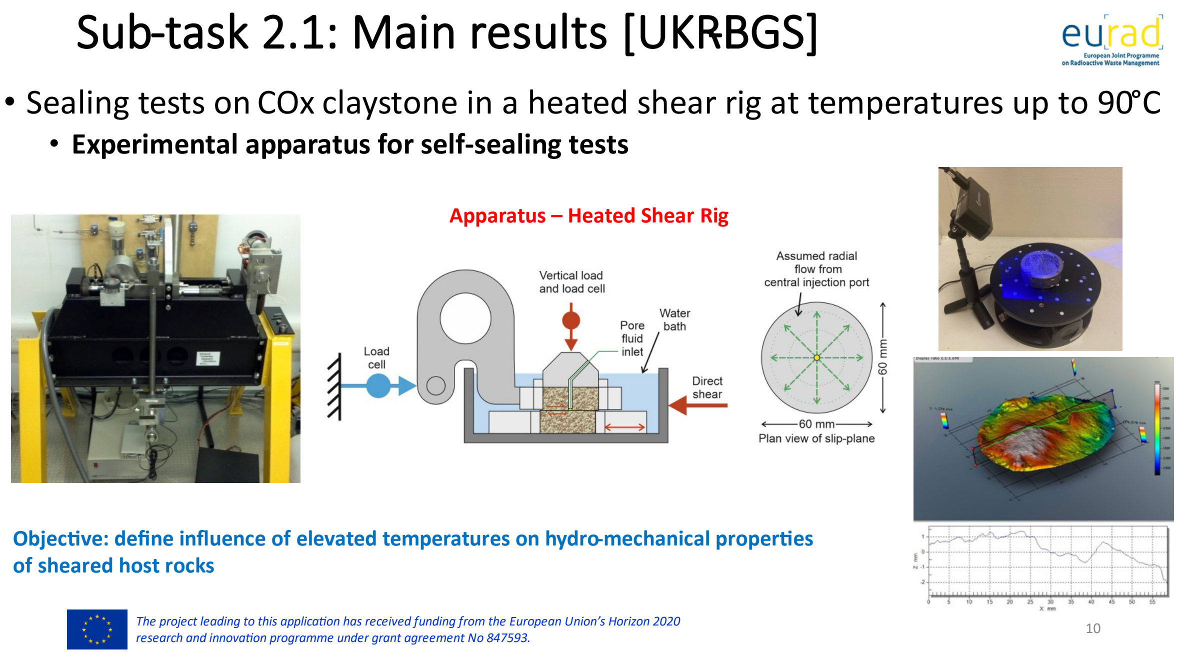
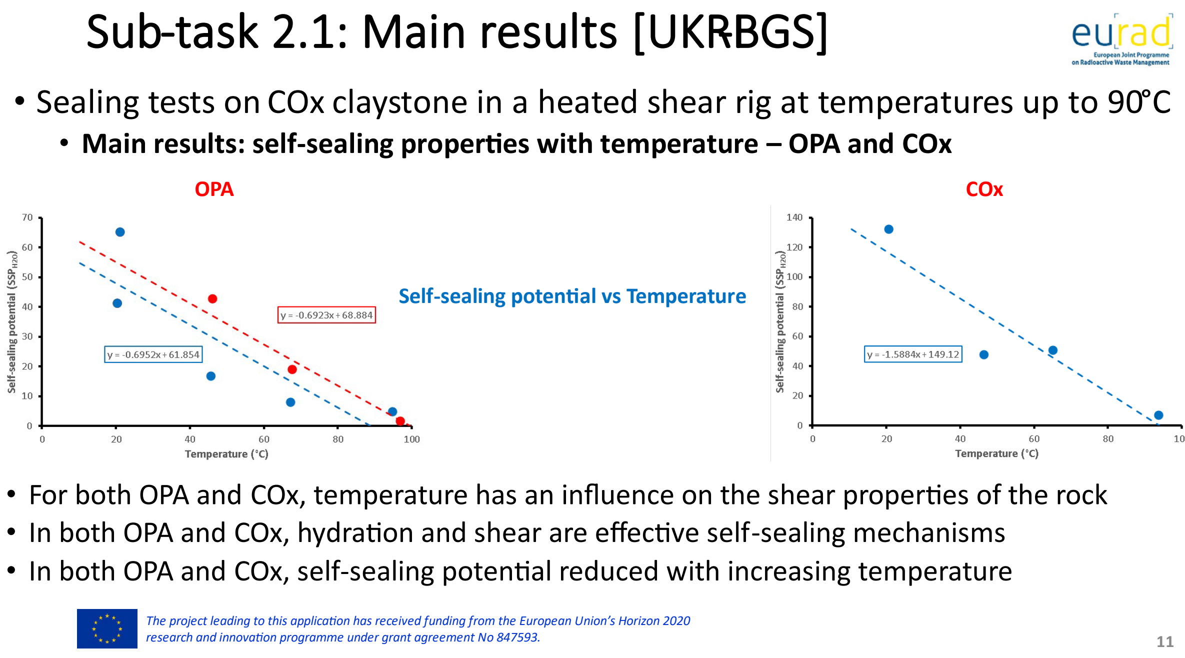


Sub-task 2.1: Main results [UKR-BGS]

- Sealing tests on COx claystone in a heated shear rig at temperatures up to 90°C
  - **Experimental apparatus for self-sealing tests**

Objective: define influence of elevated temperatures on hydro-mechanical properties of sheared host rocks

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.



Sub-task 2.1: Main results [UKRI-BGS]

- Sealing tests on COx claystone in a heated shear rig at temperatures up to 90°C
  - **Main results: self-sealing properties with temperature – OPA and COx**

- For both OPA and COx, temperature has an influence on the shear properties of the rock
- In both OPA and COx, hydration and shear are effective self-sealing mechanisms
- In both OPA and COx, self-sealing potential reduced with increasing temperature

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

Sub-task 2.2: Experiments on far field

- **Main objective:**

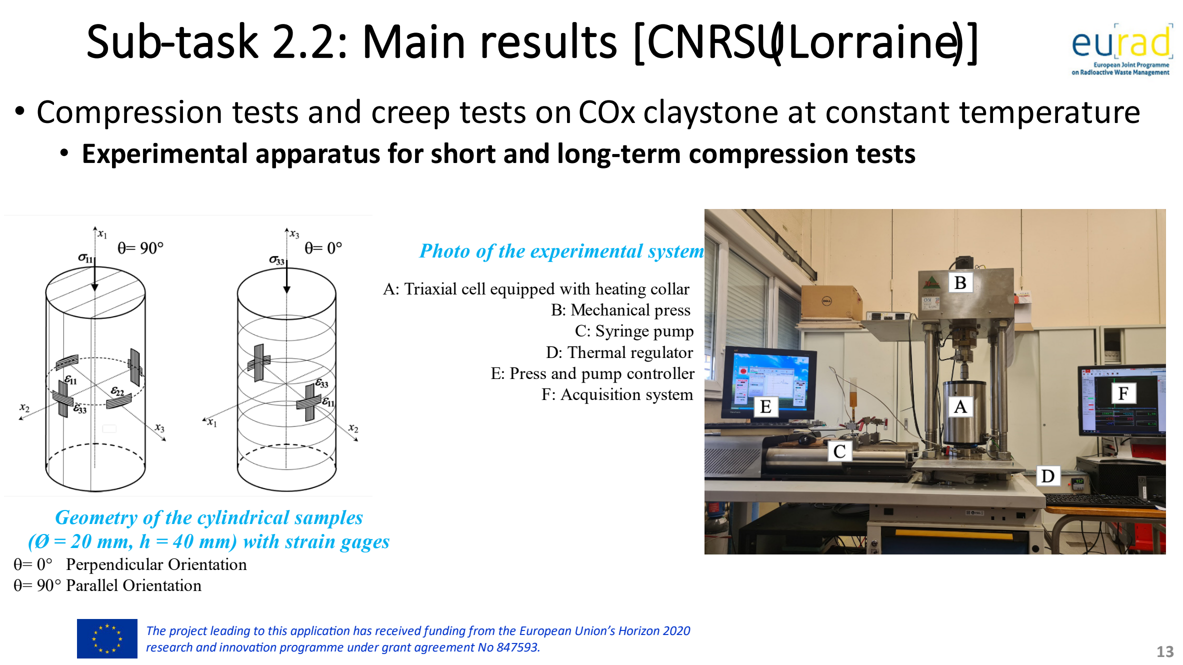
Provide answers (through lab experiments) about the effects of increased temperature on the short and long-term mechanical behaviours (deformations, elastic properties, failure strength) and on evolution of damage and intrinsic permeability due to porewater overpressures

- **Synthesis of partners works:**

	[CNRS (**ULorraine**)]	[**CEA**]	[**UKRI- BGS**]
COx	- Short-term triaxial compression tests - Triaxial creep tests		Effect of porewater overpressure on THM behaviour and permeability in load cell
OPA		Triaxial creep tests	
Boom clay			

Different monitoring tools!

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.



Sub-task 2.2: Main results [CNRSU(Lorraine)]

- Compression tests and creep tests on COx claystone at constant temperature
  - **Experimental apparatus for short and long-term compression tests**

Geometry of the cylindrical samples (Ø = 20 mm, h = 40 mm) with strain gages

θ= 0° Perpendicular Orientation
θ= 90° Parallel Orientation

Photo of the experimental system

A: Triaxial cell equipped with heating collar
B: Mechanical press
C: Syringe pump
D: Thermal regulator
E: Press and pump controller
F: Acquisition system

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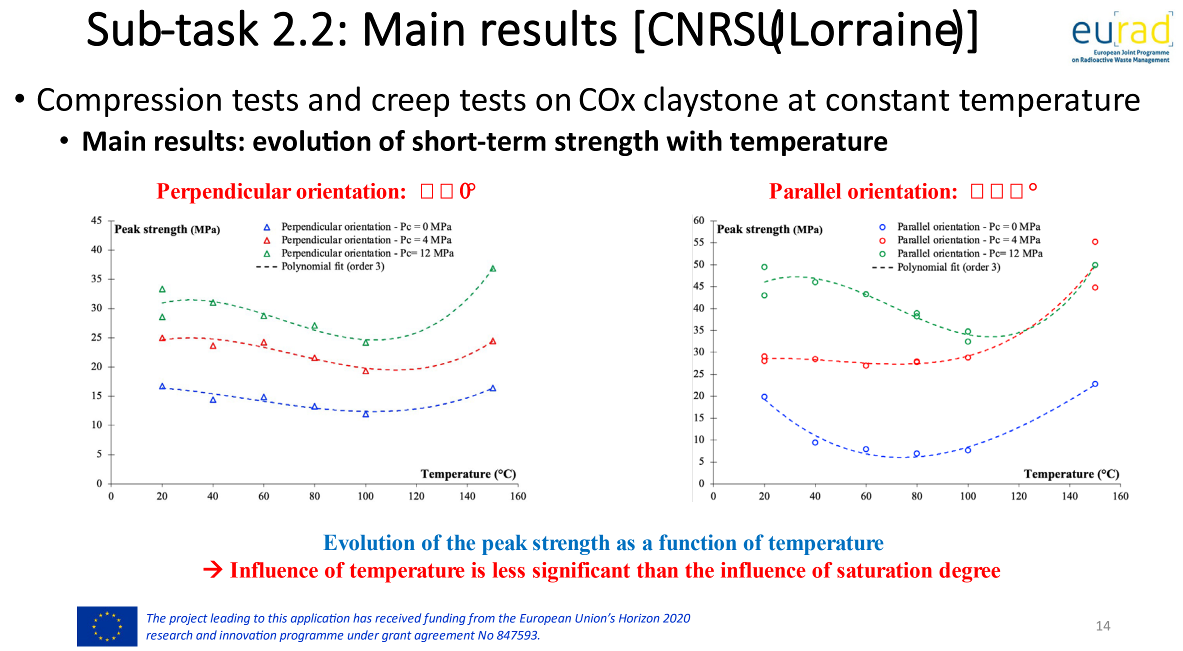

Sub-task 2.2: Main results [CNRSU(Lorraine)]

- Compression tests and creep tests on COx claystone at constant temperature
  - **Main results: evolution of short-term strength with temperature**

Perpendicular orientation: □□0°

Parallel orientation: □□□°

Evolution of the peak strength as a function of temperature

→ Influence of temperature is less significant than the influence of saturation degree

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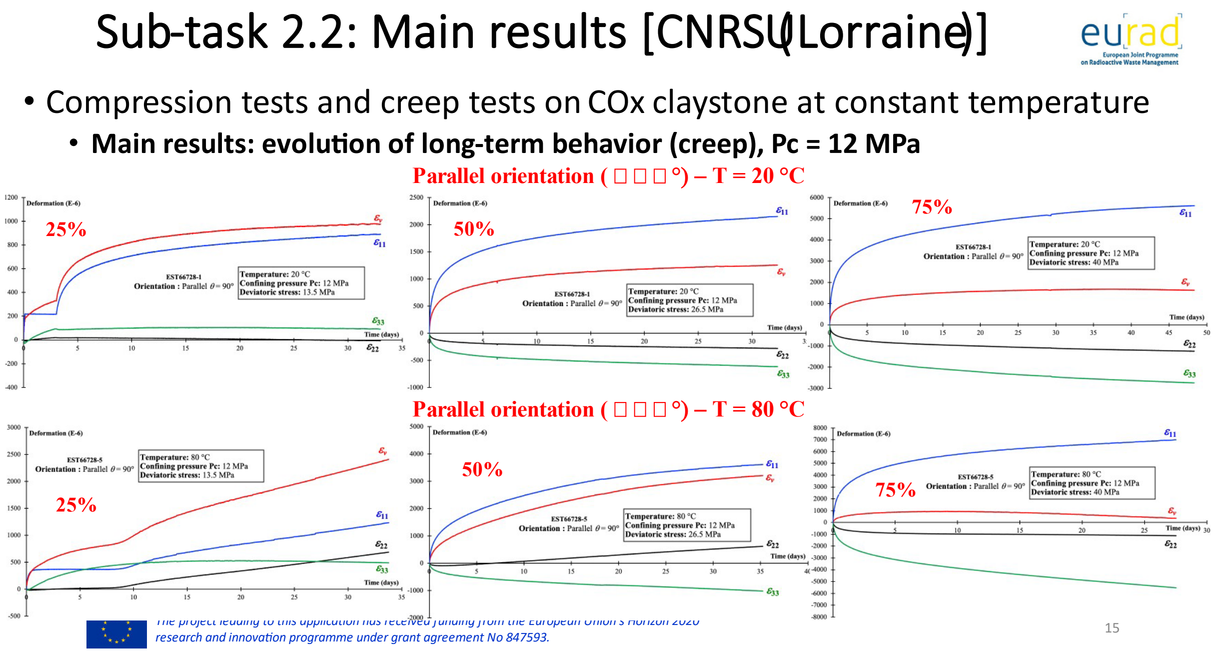


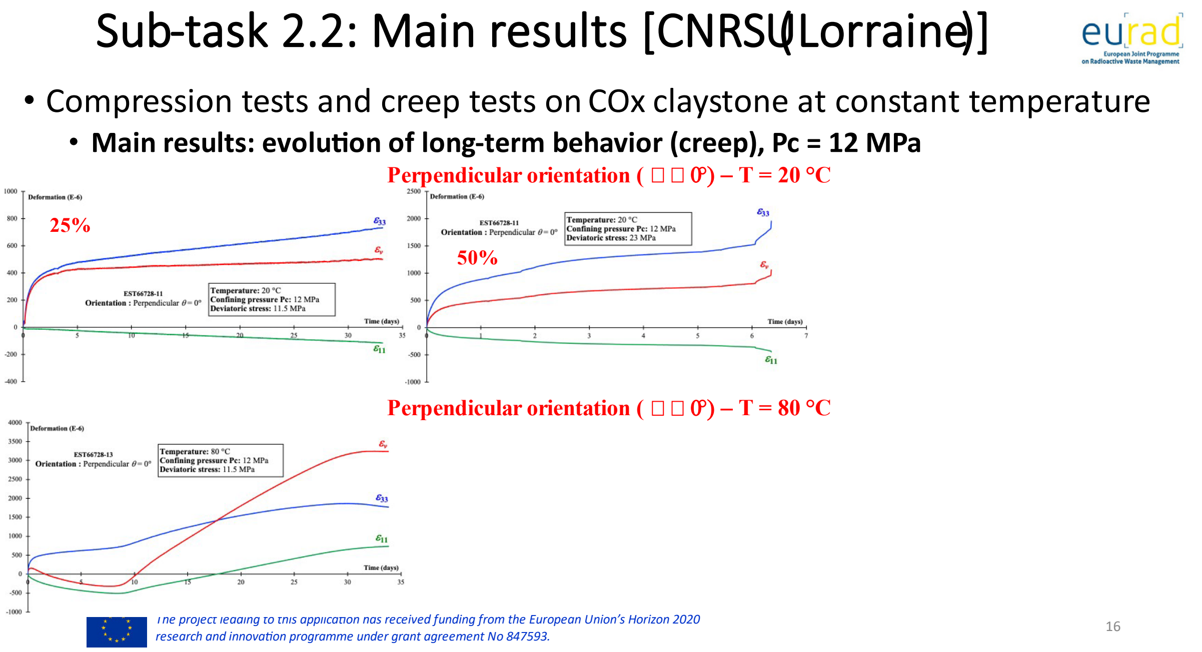
Sub-task 2.2: Main results [CNRSU(Lorraine)]

- Compression tests and creep tests on COx claystone at constant temperature
  - **Main results: evolution of long-term behavior (creep), Pc = 12 MPa**

Parallel orientation (□ □ □ °) – T = 20 °C

Parallel orientation (□ □ □ °) – T = 80 °C

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.



Sub-task 2.2: Main results [CNRSU(Lorraine)]

- Compression tests and creep tests on COx claystone at constant temperature
  - **Main results: evolution of long-term behavior (creep), Pc = 12 MPa**

Perpendicular orientation (□ □ 0°) – T = 20 °C

Perpendicular orientation (□ □ 0°) – T = 80 °C

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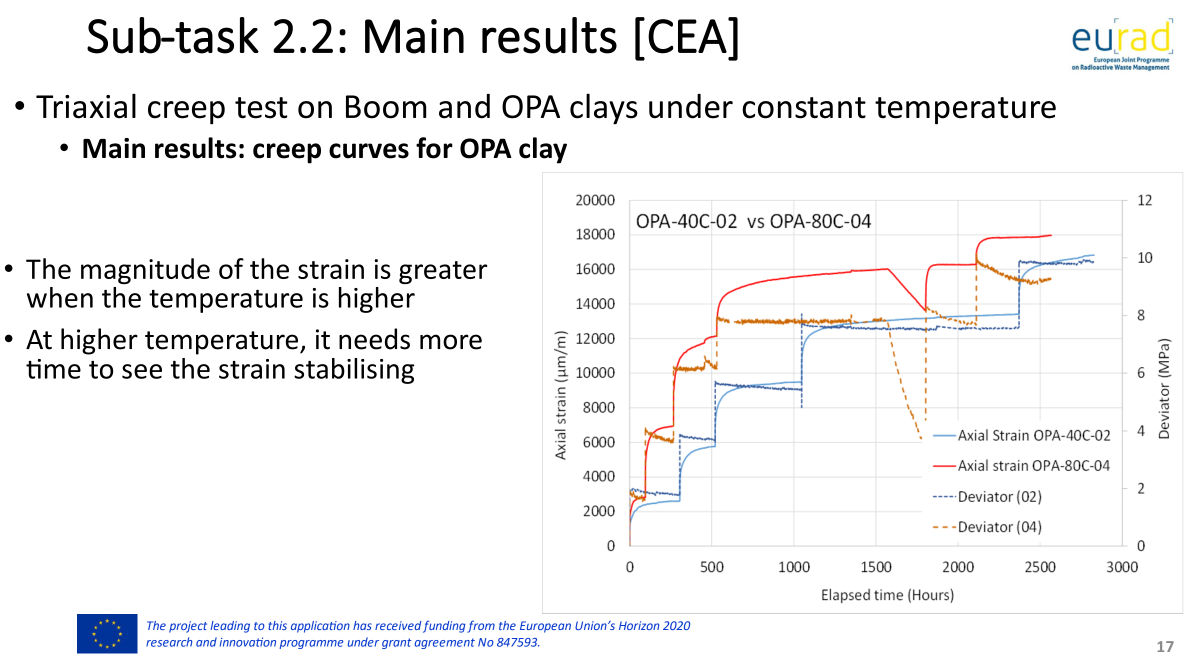

Sub-task 2.2: Main results [CEA]

- Triaxial creep test on Boom and OPA clays under constant temperature
  - **Main results: creep curves for OPA clay**

- The magnitude of the strain is greater when the temperature is higher
- At higher temperature, it needs more time to see the strain stabilising

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

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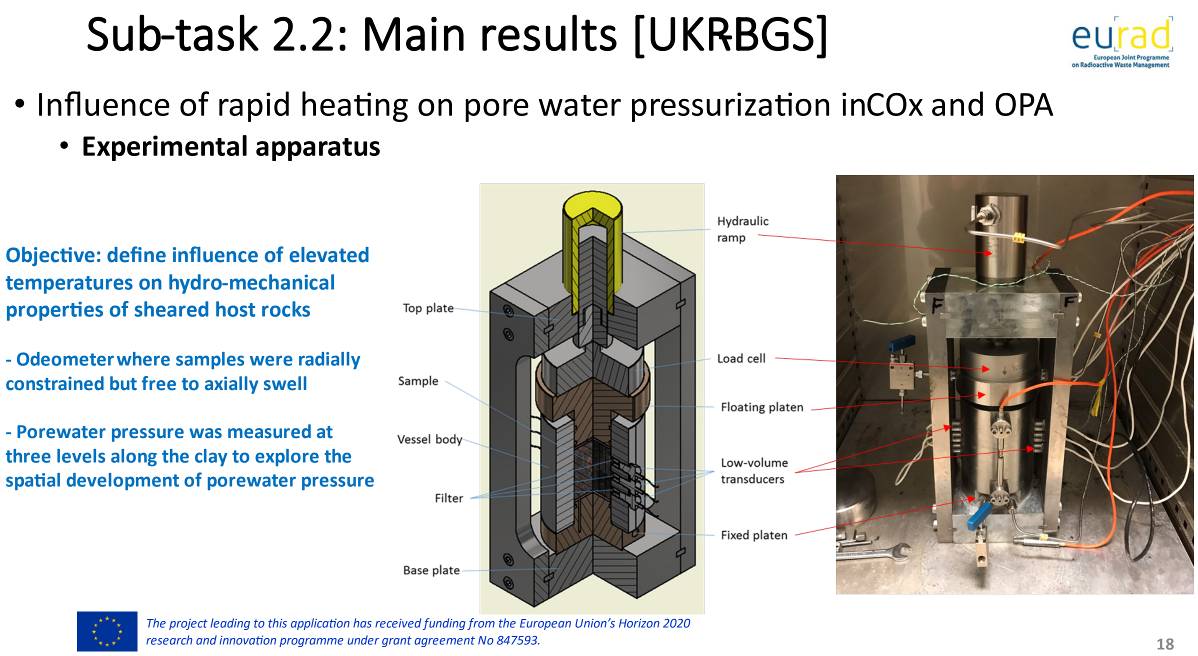

Sub-task 2.2: Main results [UKRBGS]

- Influence of rapid heating on pore water pressurization inCOx and OPA
  - **Experimental apparatus**

Objective: define influence of elevated temperatures on hydro-mechanical properties of sheared host rocks

- Odeometer where samples were radially constrained but free to axially swell

- Porewater pressure was measured at three levels along the clay to explore the spatial development of porewater pressure

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

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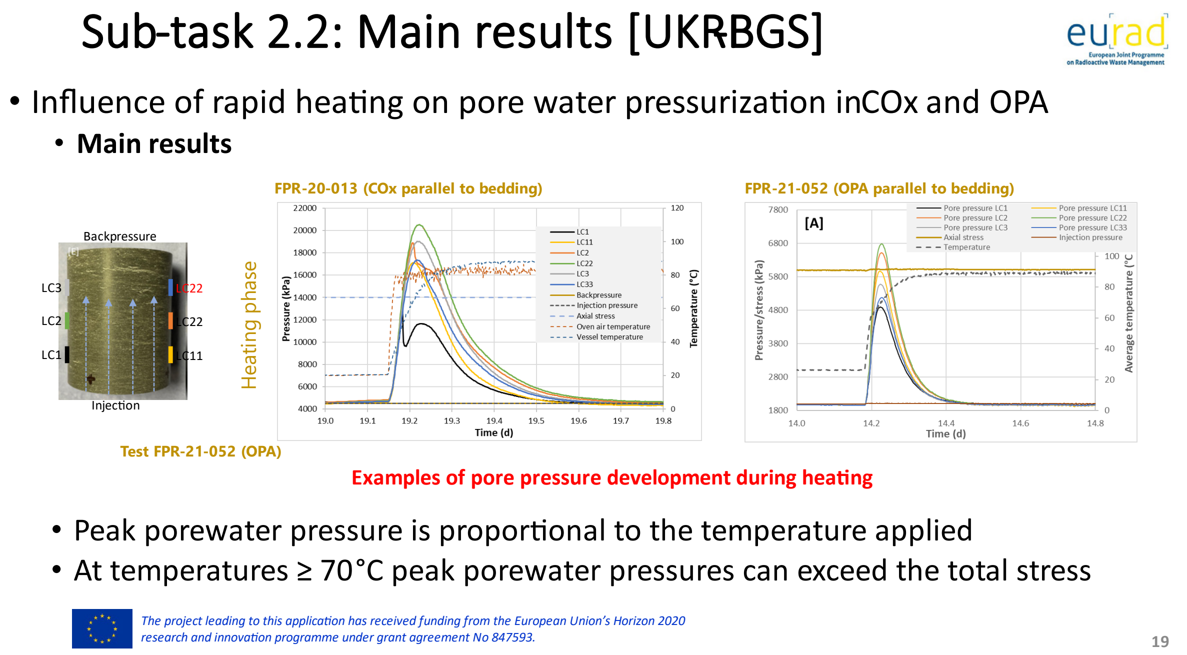

Sub-task 2.2: Main results [UKRBGS]

- Influence of rapid heating on pore water pressurization inCOx and OPA
  - **Main results**

FPR-20-013 (COx parallel to bedding)

FPR-21-052 (OPA parallel to bedding)

Test FPR-21-052 (OPA)

Examples of pore pressure development during heating

- Peak porewater pressure is proportional to the temperature applied
- At temperatures ≥ 70°C peak porewater pressures can exceed the total stress

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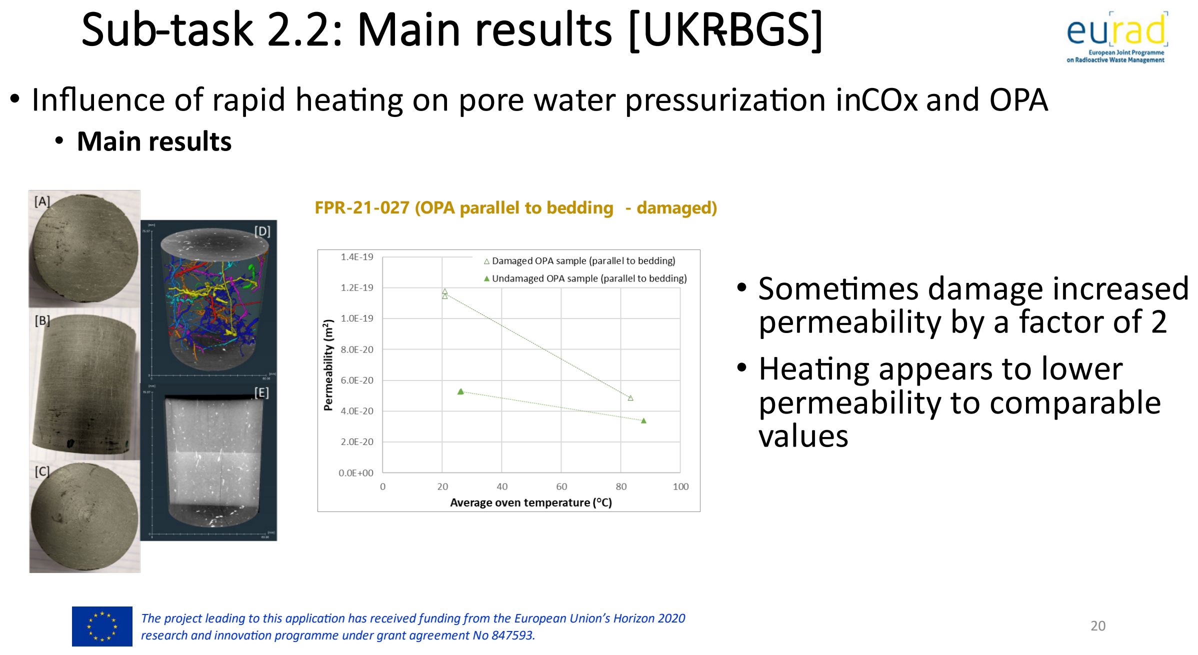

Sub-task 2.2: Main results [UKRBGS]

- Influence of rapid heating on pore water pressurization inCOx and OPA
  - **Main results**

FPR-21-027 (OPA parallel to bedding - damaged)

- Sometimes damage increased permeability by a factor of 2
- Heating appears to lower permeability to comparable values

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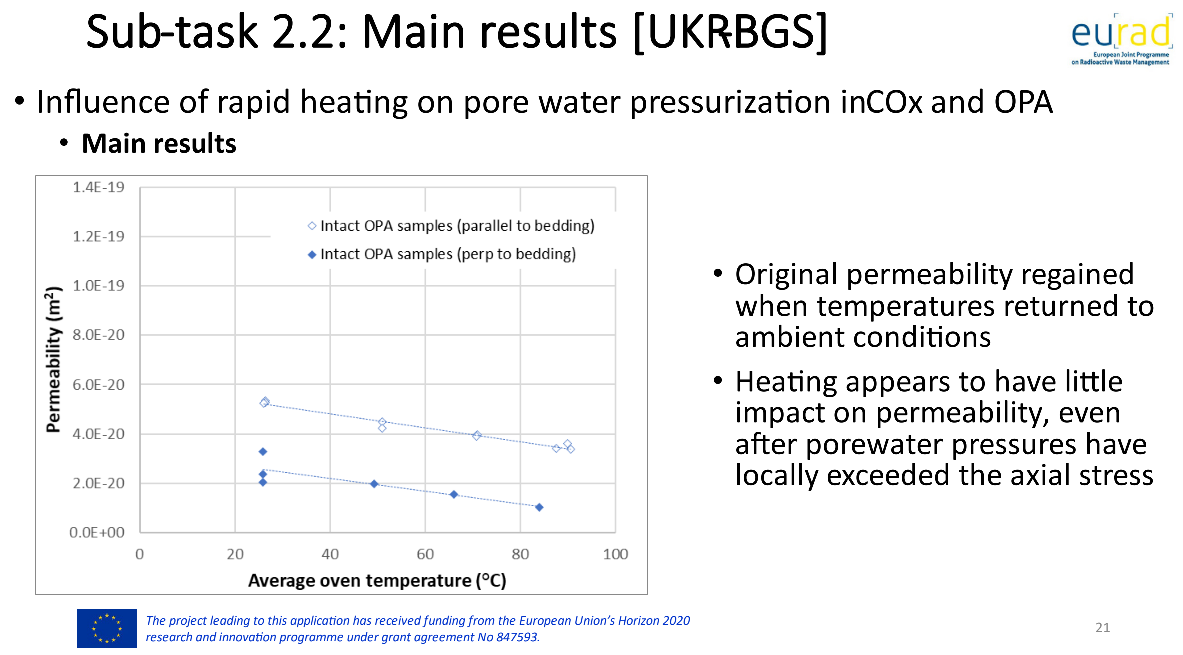

Sub-task 2.2: Main results [UKRBGS]

- Influence of rapid heating on pore water pressurization inCOx and OPA
  - **Main results**

- Original permeability regained when temperatures returned to ambient conditions
- Heating appears to have little impact on permeability, even after porewater pressures have locally exceeded the axial stress

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

HITEC – Task 2: Clay host rock
General conclusions

- **Sub-task 2.1: Experiments near field with EDZ**
  - Self-sealing reduces partially the permeability of the COx claystone (10^{-18}-10^{-19} m^2) compared to the initial permeability of the healthy claystone (10^{-20}-10^{-21} m^2)
  - To have an effective sealing, it is necessary to have a carbonate content lower than 40%
  - Self-sealing is an efficient mechanism, whatever the sample orientation or crack width
  - There is no significant impact of temperature on the self-sealing process
  - The effectiveness of self-sealing processes as a result of hydration and shear was seen to reduce significantly at elevated temperatures

- Self-sealing is always an efficient mechanism if the clay content is high enough. Its effectiveness is only reduced at elevated temperatures if it is associated with significant crack shearing
- These results give confidence to the positive impact of the self -sealing process on the restoration of the initial sealing properties of the clay host rock

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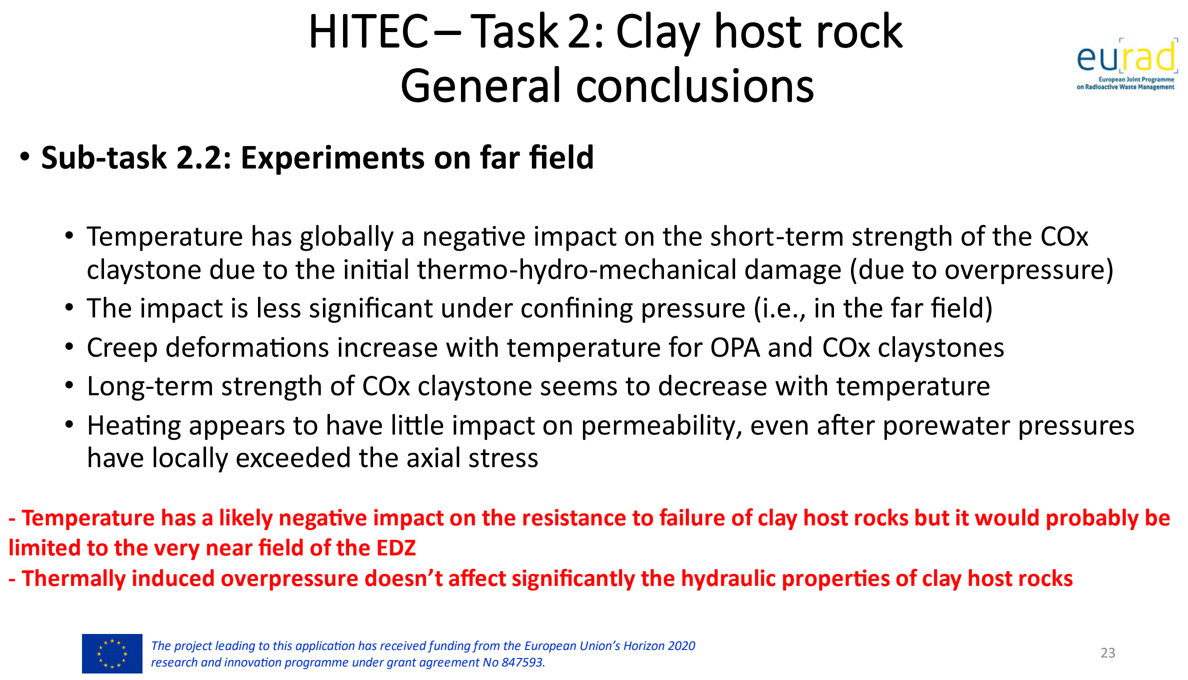


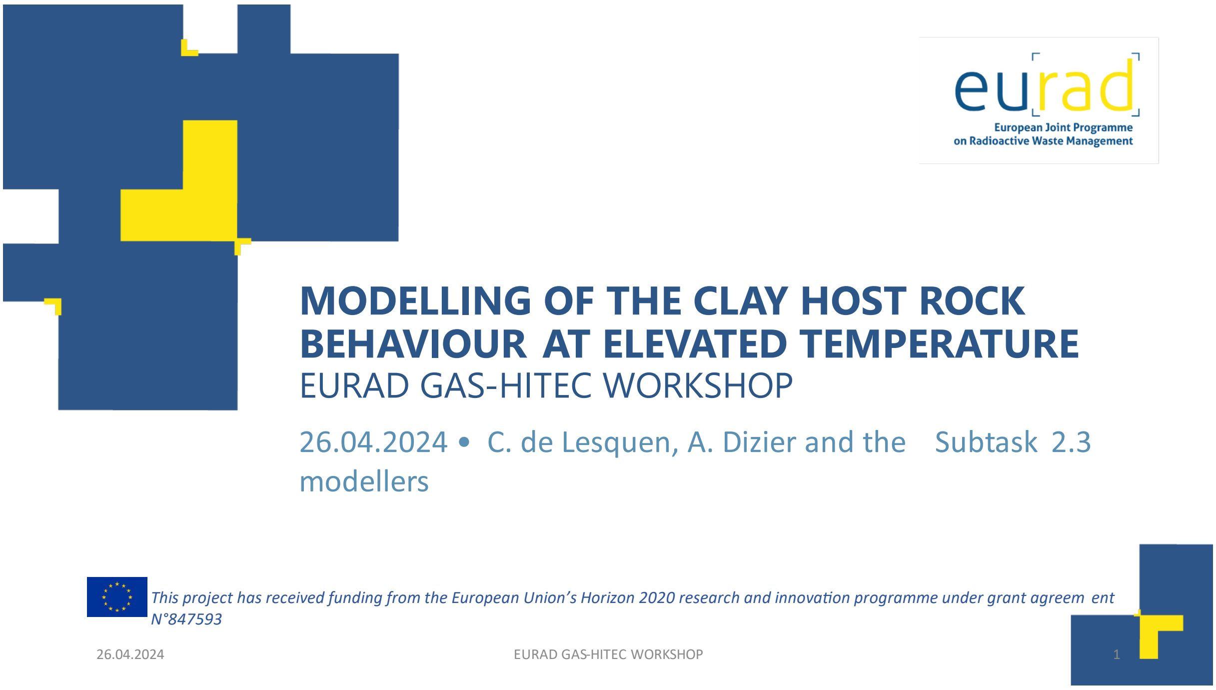
HITEC – Task 2: Clay host rock
General conclusions

- **Sub-task 2.2: Experiments on far field**
  - Temperature has globally a negative impact on the short-term strength of the COx claystone due to the initial thermo-hydro-mechanical damage (due to overpressure)
  - The impact is less significant under confining pressure (i.e., in the far field)
  - Creep deformations increase with temperature for OPA and COx claystones
  - Long-term strength of COx claystone seems to decrease with temperature
  - Heating appears to have little impact on permeability, even after porewater pressures have locally exceeded the axial stress

- Temperature has a likely negative impact on the resistance to failure of clay host rocks but it would probably be limited to the very near field of the EDZ
- Thermally induced overpressure doesn't affect significantly the hydraulic properties of clay host rocks

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

1.3 Modeling of clayey host rock mechanics at elevated temperature



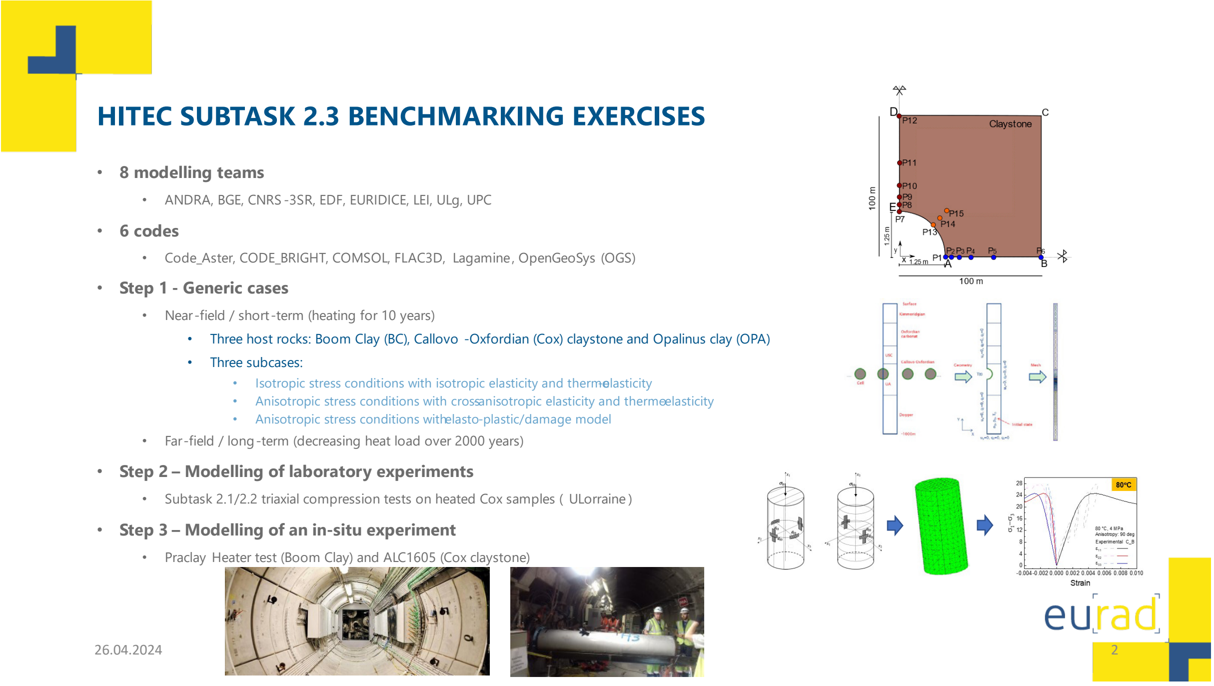
MODELLING OF THE CLAY HOST ROCK BEHAVIOUR AT ELEVATED TEMPERATURE

EURAD GAS-HITEC WORKSHOP

26.04.2024 • C. de Lesquen, A. Dizier and the Subtask 2.3 modellers

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°847593

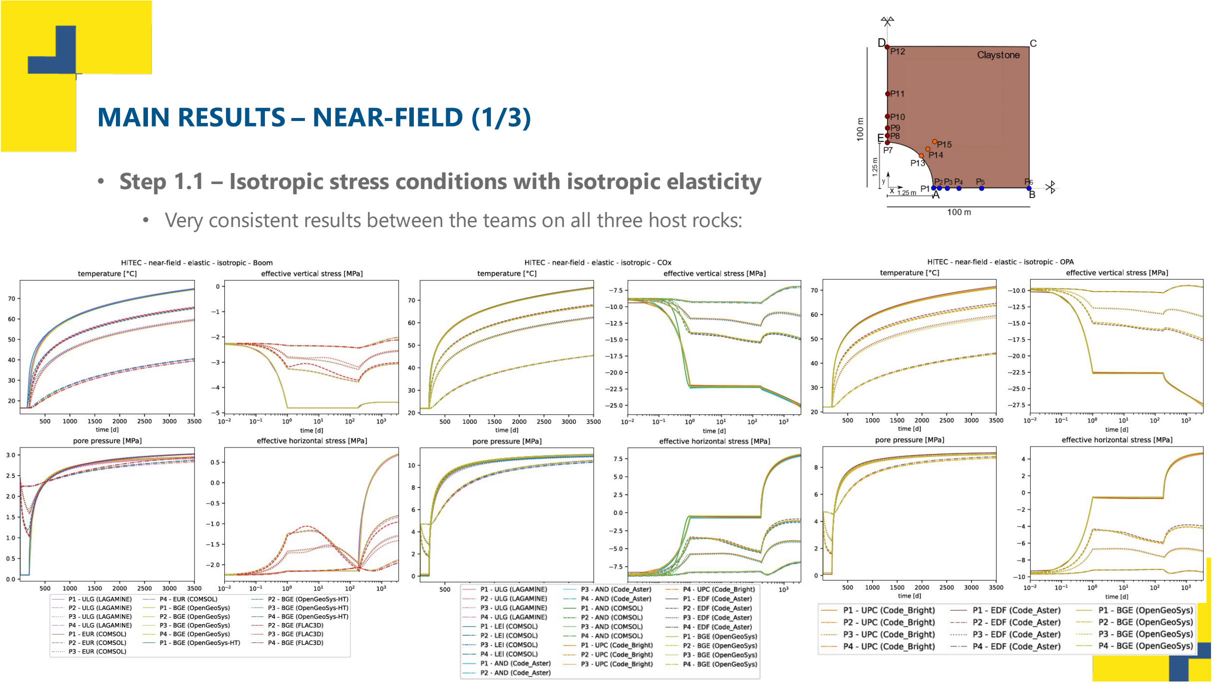
26.04.2024 EURAD GAS-HITEC WORKSHOP 1



HITEC SUBTASK 2.3 BENCHMARKING EXERCISES

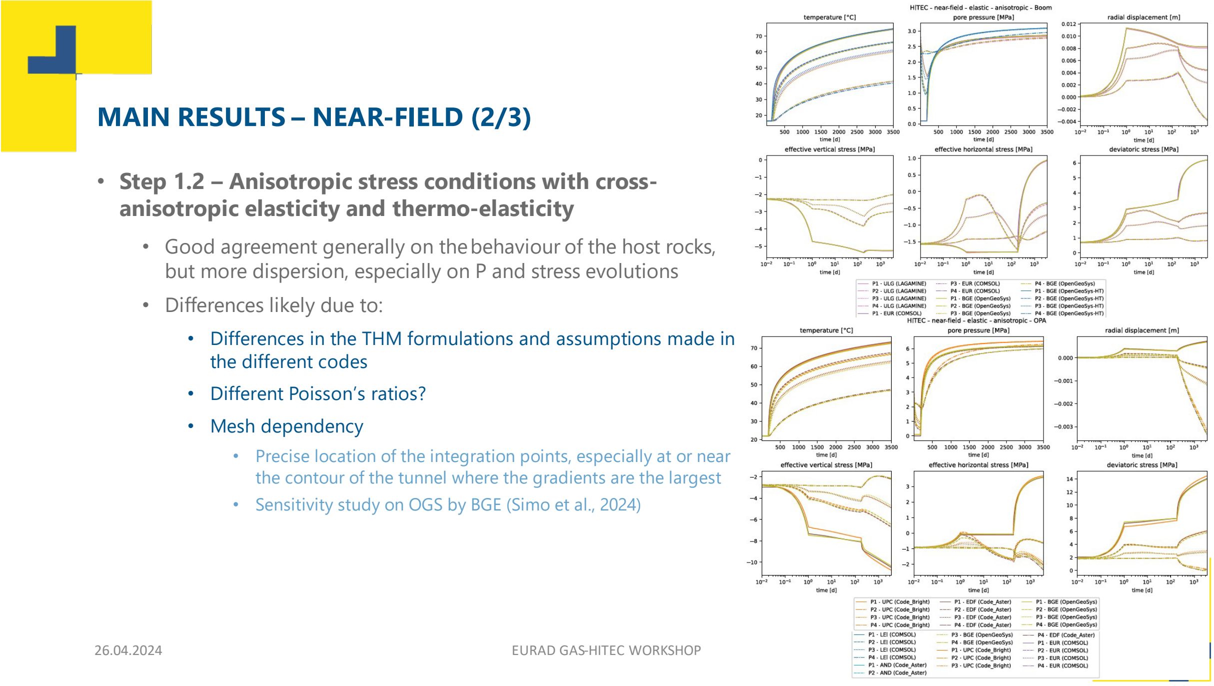
- **8 modelling teams**
  - ANDRA, BGE, CNRS-3SR, EDF, EURIDICE, LEI, ULg, UPC
- **6 codes**
  - Code_Aster, CODE_BRIGHT, COMSOL, FLAC3D, Lagamine, OpenGeoSys (OGS)
- **Step 1 - Generic cases**
  - Near-field / short-term (heating for 10 years)
    - Three host rocks: Boom Clay (BC), Callovo-Oxfordian (Cox) claystone and Opalinus clay (OPA)
    - Three subcases:
      - Isotropic stress conditions with isotropic elasticity and thermoelasticity
      - Anisotropic stress conditions with cross-anisotropic elasticity and thermoelasticity
      - Anisotropic stress conditions with elasto-plastic/damage model
  - Far-field / long-term (decreasing heat load over 2000 years)
- **Step 2 – Modelling of laboratory experiments**
  - Subtask 2.1/2.2 triaxial compression tests on heated Cox samples (ULorraine)
- **Step 3 – Modelling of an in-situ experiment**
  - Praclay Heater test (Boom Clay) and ALC1605 (Cox claystone)

26.04.2024 2



MAIN RESULTS – NEAR-FIELD (1/3)

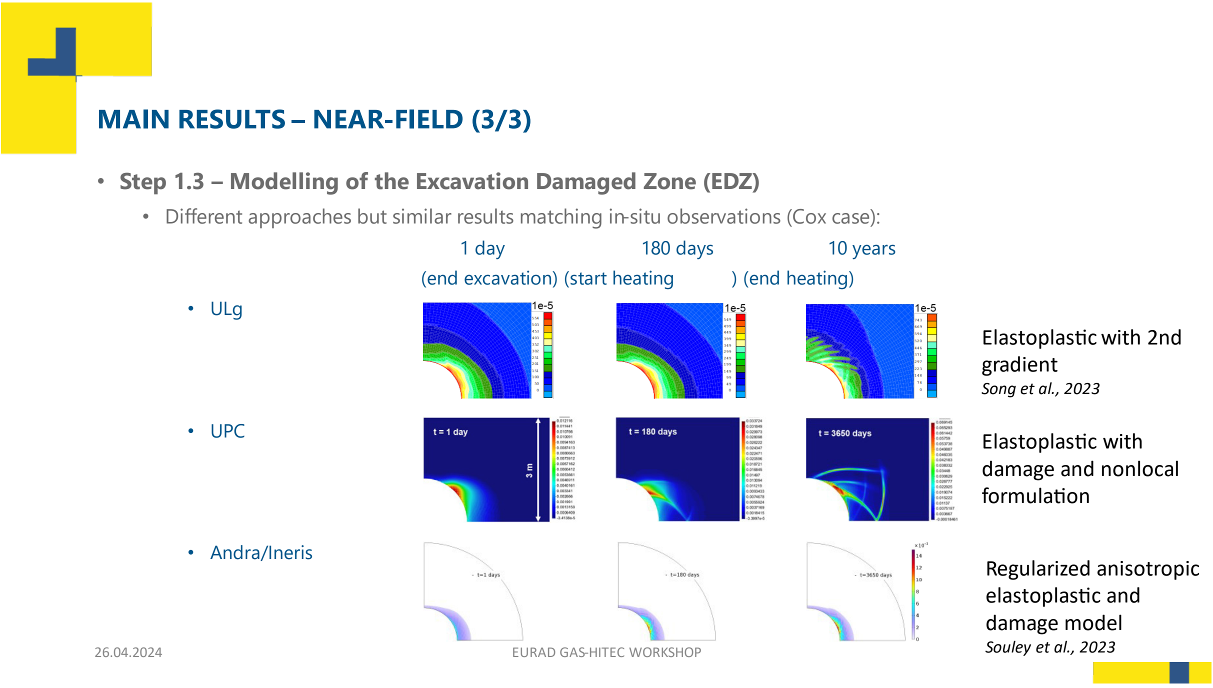
- **Step 1.1 – Isotropic stress conditions with isotropic elasticity**
  - Very consistent results between the teams on all three host rocks:



MAIN RESULTS – NEAR-FIELD (2/3)

- **Step 1.2 – Anisotropic stress conditions with cross-anisotropic elasticity and thermo-elasticity**
  - Good agreement generally on the behaviour of the host rocks, but more dispersion, especially on P and stress evolutions
  - Differences likely due to:
    - Differences in the THM formulations and assumptions made in the different codes
    - Different Poisson's ratios?
    - Mesh dependency
      - Precise location of the integration points, especially at or near the contour of the tunnel where the gradients are the largest
      - Sensitivity study on OGS by BGE (Simo et al., 2024)

26.04.2024 EURAD GAS-HITEC WORKSHOP



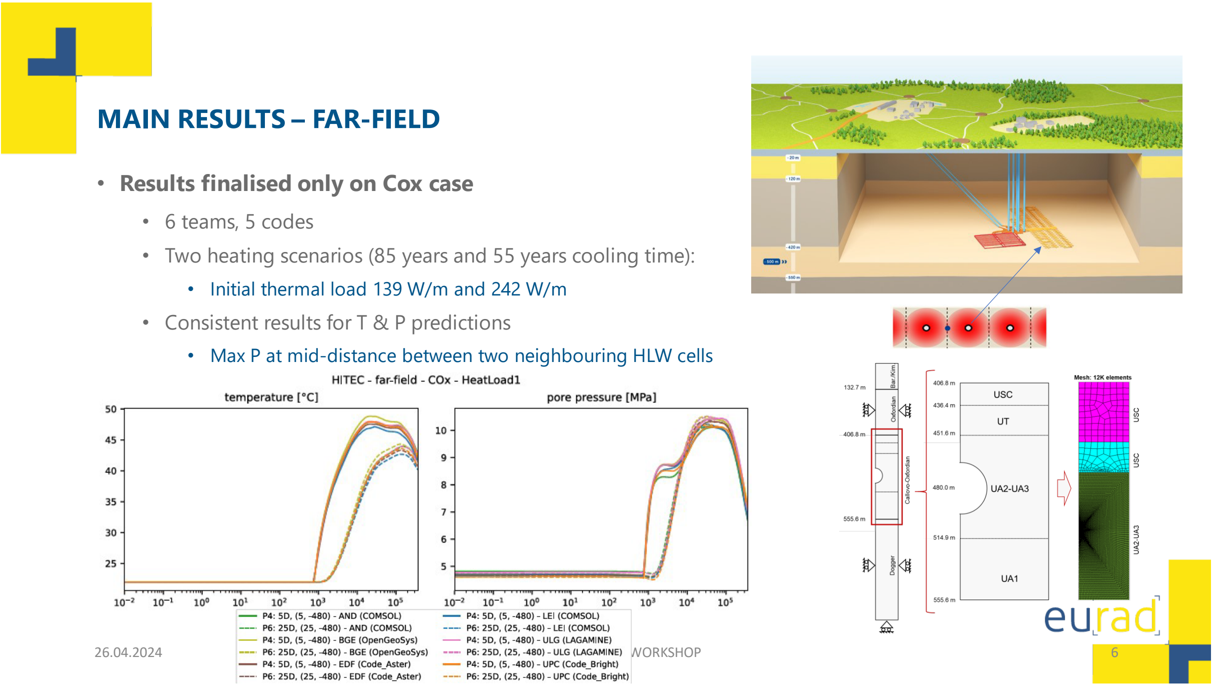
MAIN RESULTS – NEAR-FIELD (3/3)

- **Step 1.3 – Modelling of the Excavation Damaged Zone (EDZ)**
  - Different approaches but similar results matching in-situ observations (Cox case):
    - ULg
    - UPC
    - Andra/Ineris

Elastoplastic with 2nd gradient
Song et al., 2023

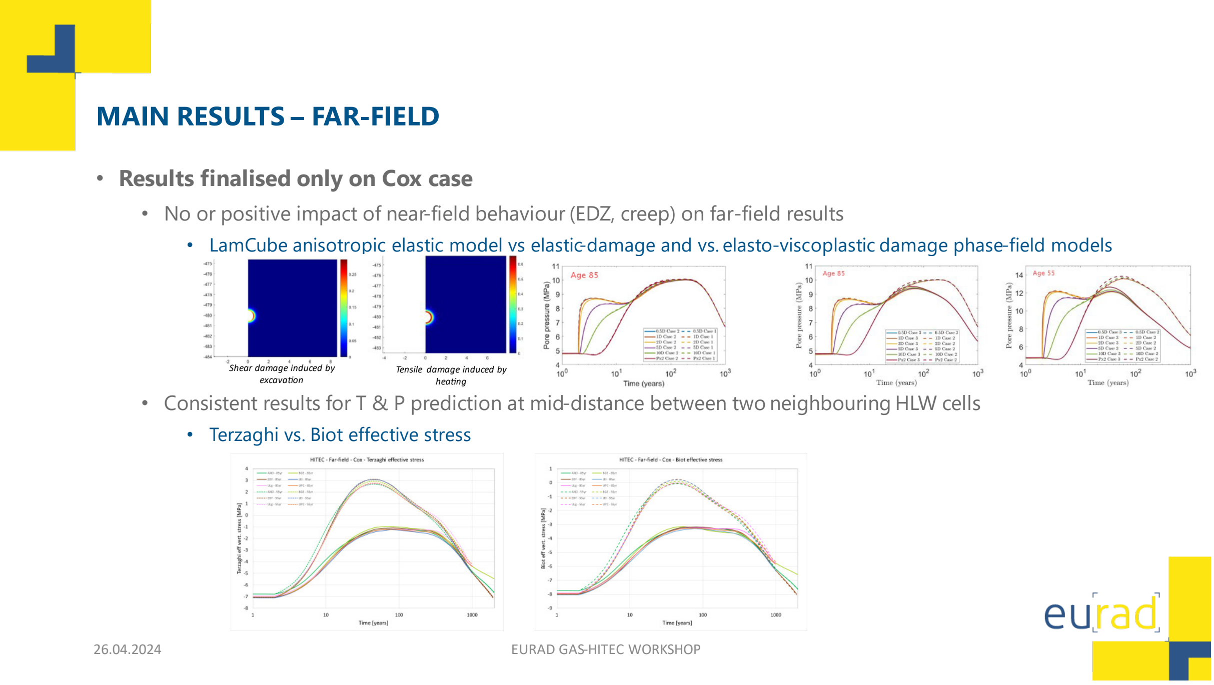
Elastoplastic with damage and nonlocal formulation

Regularized anisotropic elastoplastic and damage model
Souley et al., 2023



MAIN RESULTS – FAR-FIELD

- **Results finalised only on Cox case**
  - 6 teams, 5 codes
  - Two heating scenarios (85 years and 55 years cooling time):
    - Initial thermal load 139 W/m and 242 W/m
  - Consistent results for T & P predictions
    - Max P at mid-distance between two neighbouring HLW cells



MAIN RESULTS – FAR-FIELD

- **Results finalised only on Cox case**
  - No or positive impact of near-field behaviour (EDZ, creep) on far-field results
    - LamCube anisotropic elastic model vs elastic-damage and vs. elasto-viscoplastic damage phase-field models

Shear damage induced by excavation

Tensile damage induced by heating

  - Consistent results for T & P prediction at mid-distance between two neighbouring HLW cells
    - Terzaghi vs. Biot effective stress

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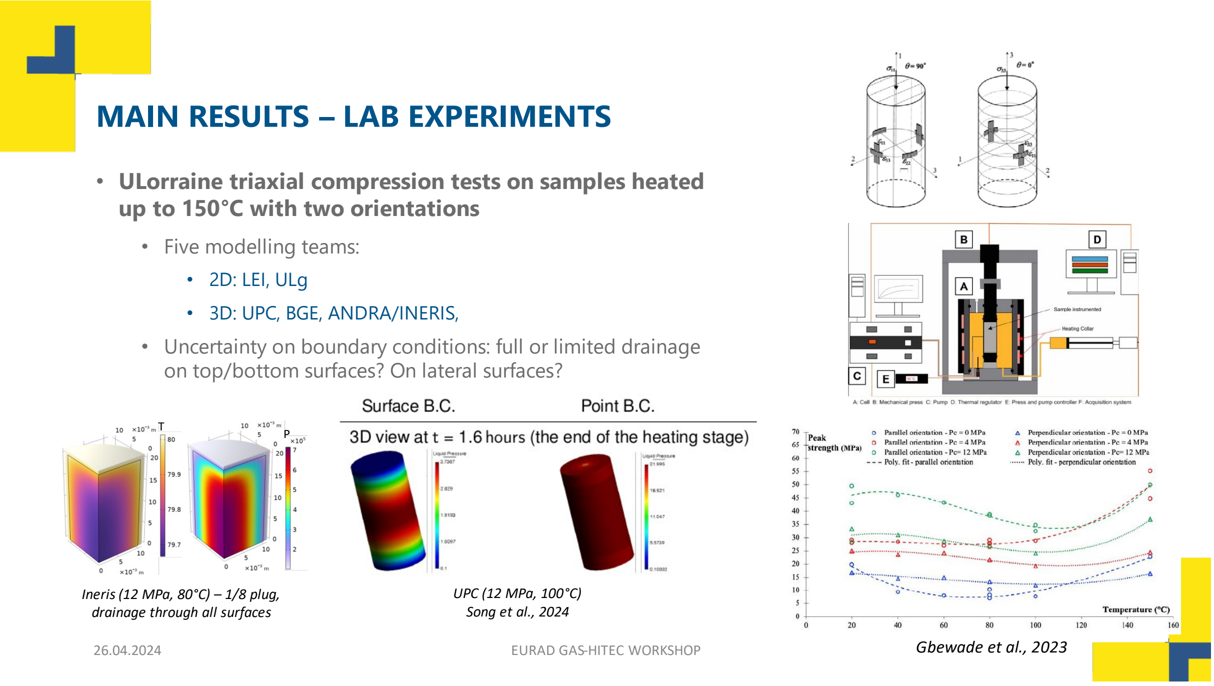

MAIN RESULTS – LAB EXPERIMENTS

- **ULorraine triaxial compression tests on samples heated up to 150°C with two orientations**
  - Five modelling teams:
    - 2D: LEI, ULg
    - 3D: UPC, BGE, ANDRA/INERIS,
  - Uncertainty on boundary conditions: full or limited drainage on top/bottom surfaces? On lateral surfaces?

Surface B.C. Point B.C.

3D view at t = 1.6 hours (the end of the heating stage)

Ineris (12 MPa, 80°C) – 1/8 plug, drainage through all surfaces

UPC (12 MPa, 100°C) Song et al., 2024

Gbewade et al., 2023

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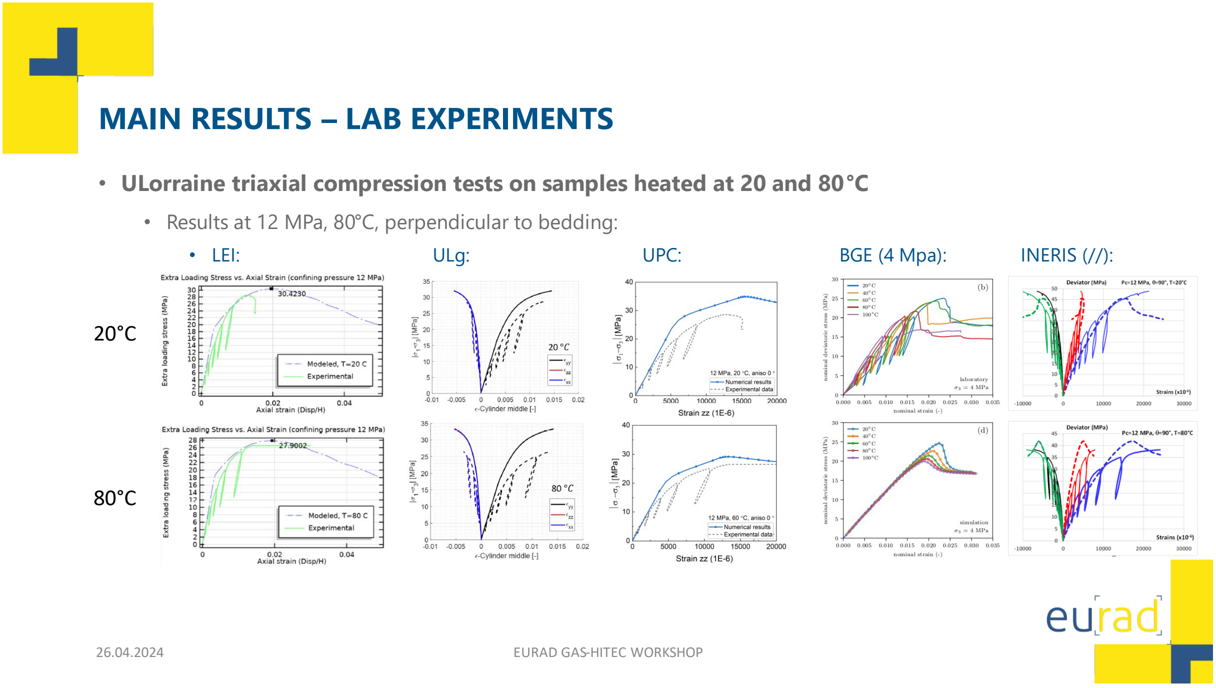

MAIN RESULTS – LAB EXPERIMENTS

- **ULorraine triaxial compression tests on samples heated at 20 and 80°C**
  - Results at 12 MPa, 80°C, perpendicular to bedding:
    - LEI: ULg: UPC: BGE (4 Mpa): INERIS (//):

20°C

80°C

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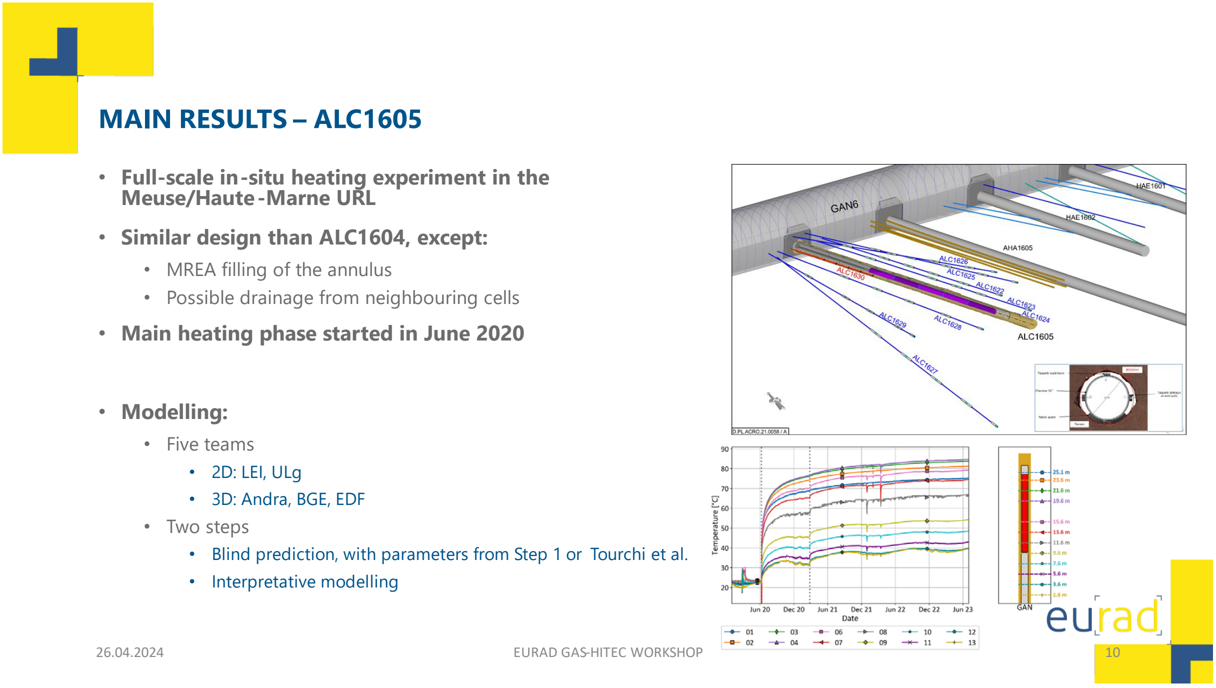

MAIN RESULTS – ALC1605

- **Full-scale in-situ heating experiment in the Meuse/Haute-Marne URL**
- **Similar design than ALC1604, except:**
  - MREA filling of the annulus
  - Possible drainage from neighbouring cells
- **Main heating phase started in June 2020**
- **Modelling:**
  - Five teams
    - 2D: LEI, ULg
    - 3D: Andra, BGE, EDF
  - Two steps
    - Blind prediction, with parameters from Step 1 or Tourchi et al.
    - Interpretative modelling

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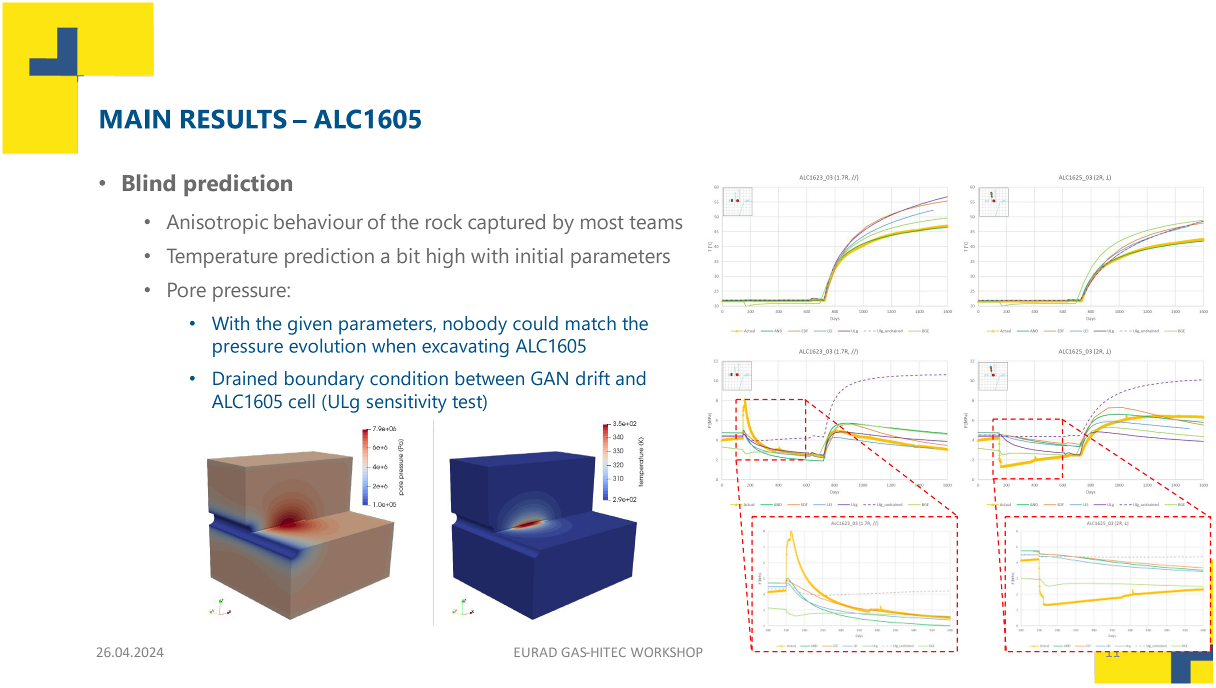

MAIN RESULTS – ALC1605

- **Blind prediction**
  - Anisotropic behaviour of the rock captured by most teams
  - Temperature prediction a bit high with initial parameters
  - Pore pressure:
    - With the given parameters, nobody could match the pressure evolution when excavating ALC1605
    - Drained boundary condition between GAN drift and ALC1605 cell (ULg sensitivity test)

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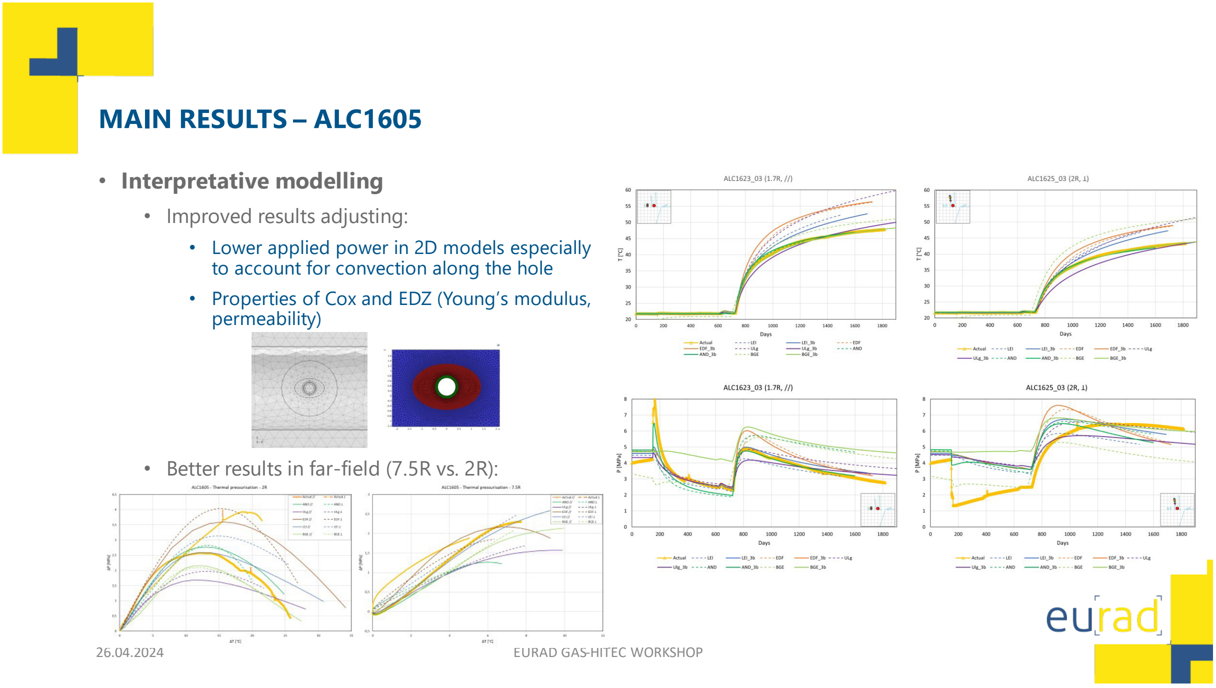

MAIN RESULTS – ALC1605

- **Interpretative modelling**
  - Improved results adjusting:
    - Lower applied power in 2D models especially to account for convection along the hole
    - Properties of Cox and EDZ (Young's modulus, permeability)
  - Better results in far-field (7.5R vs. 2R):

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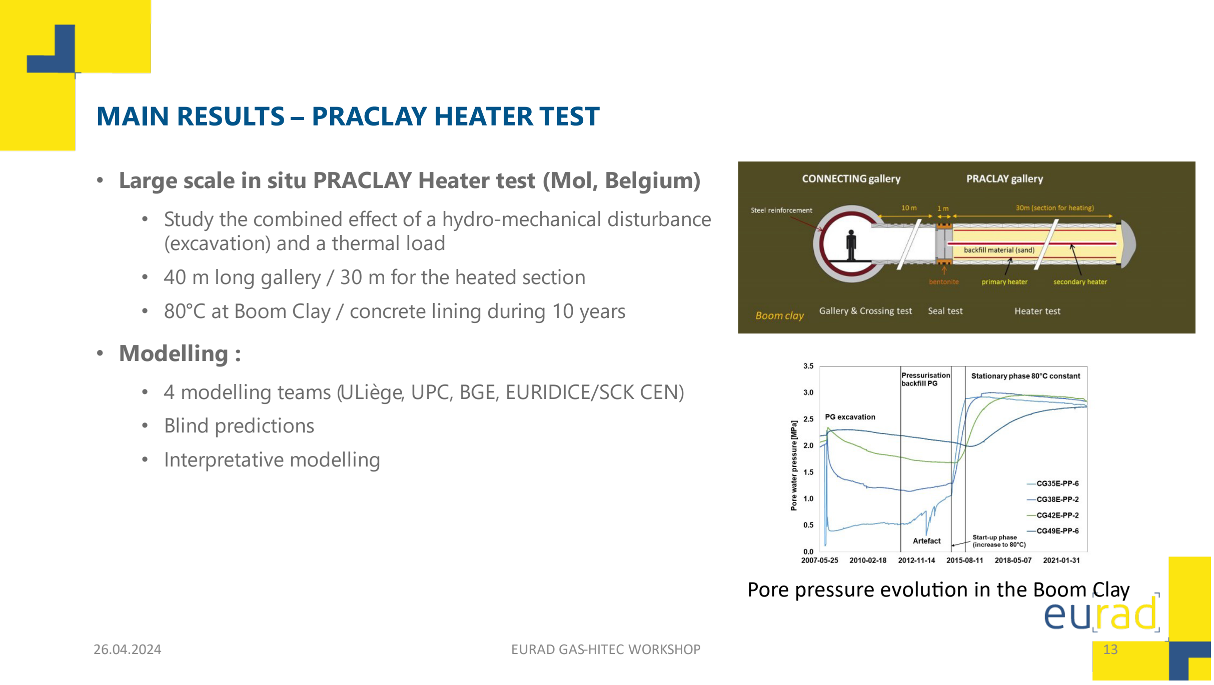
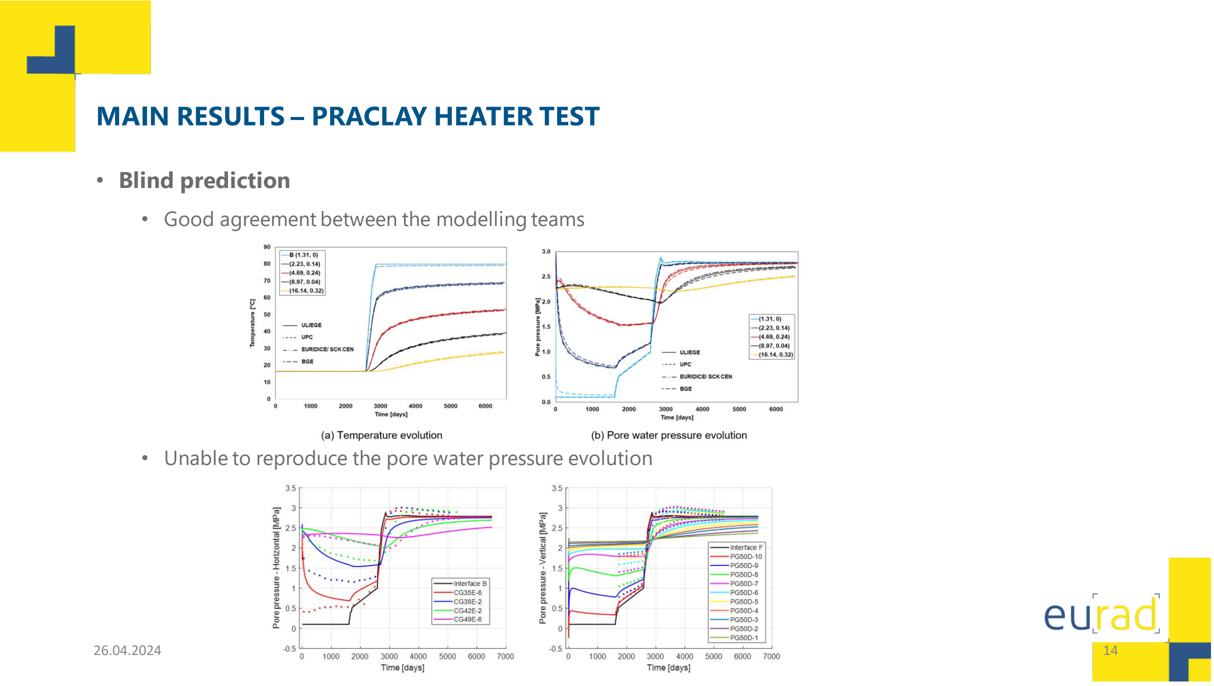


MAIN RESULTS – PRACLAY HEATER TEST

- **Large scale in situ PRACLAY Heater test (Mol, Belgium)**
  - Study the combined effect of a hydro-mechanical disturbance (excavation) and a thermal load
  - 40 m long gallery / 30 m for the heated section
  - 80°C at Boom Clay / concrete lining during 10 years
- **Modelling :**
  - 4 modelling teams (ULiège, UPC, BGE, EURIDICE/SCK CEN)
  - Blind predictions
  - Interpretative modelling

Pore pressure evolution in the Boom Clay

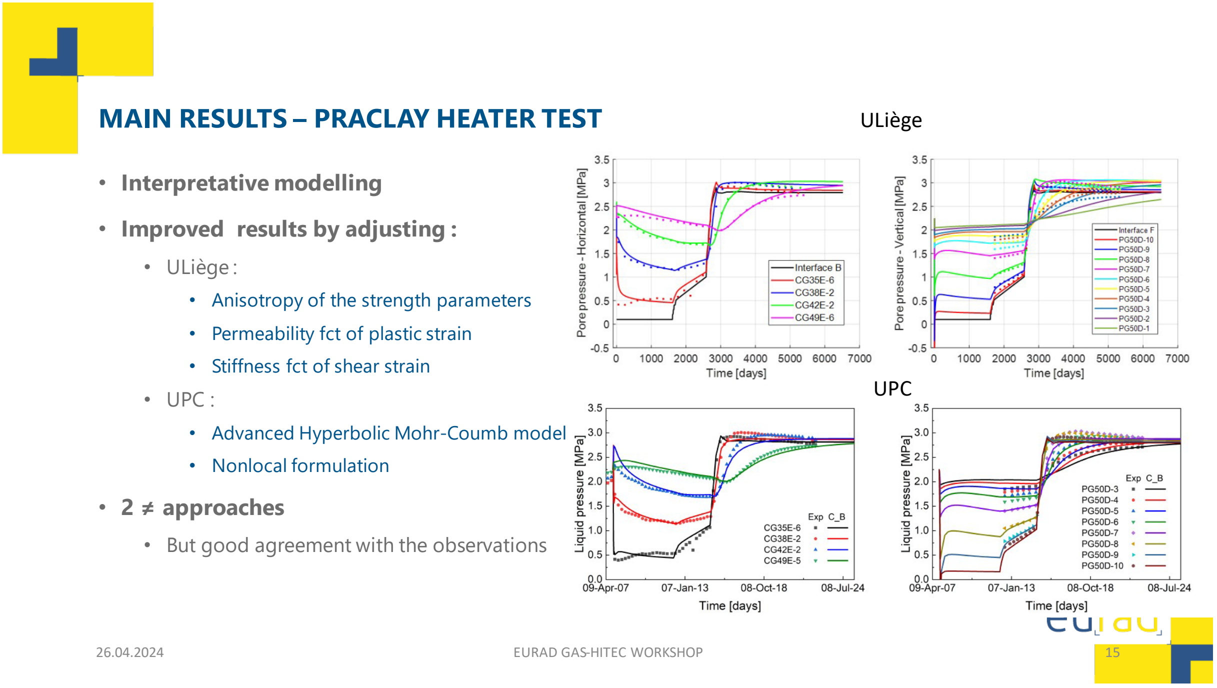


MAIN RESULTS – PRACLAY HEATER TEST

- **Blind prediction**
  - Good agreement between the modelling teams

(a) Temperature evolution (b) Pore water pressure evolution

  - Unable to reproduce the pore water pressure evolution

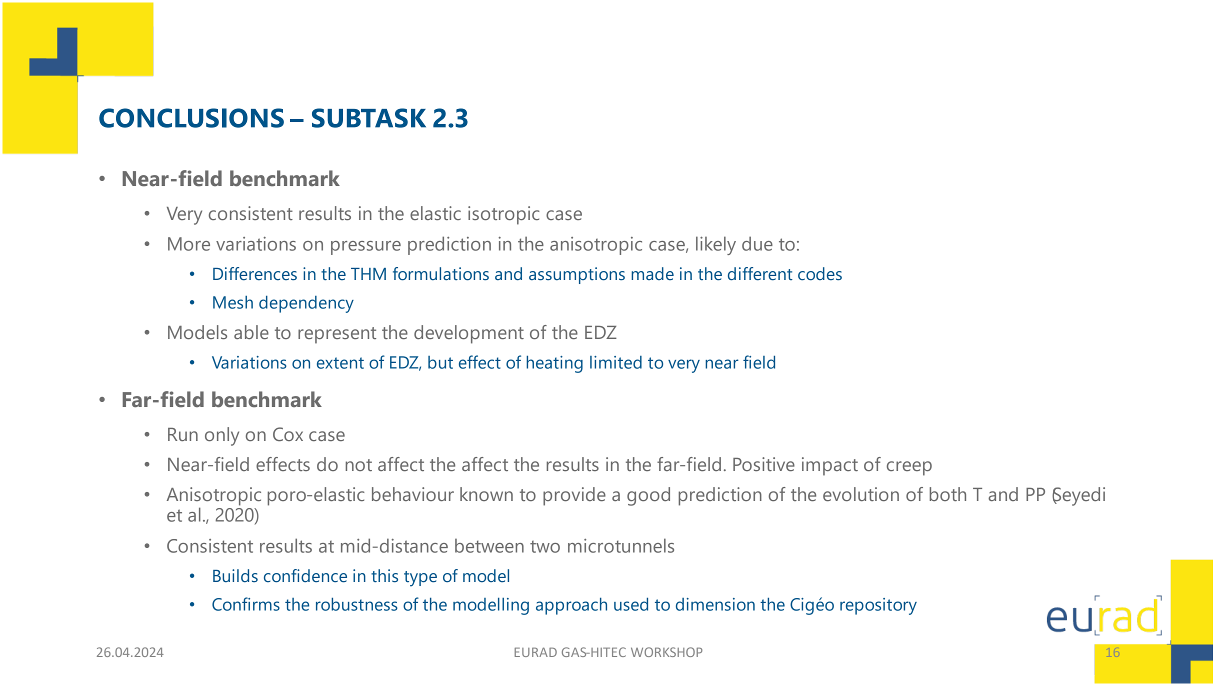


MAIN RESULTS – PRACLAY HEATER TEST

- **Interpretative modelling**
- **Improved results by adjusting :**
  - ULiège :
    - Anisotropy of the strength parameters
    - Permeability fct of plastic strain
    - Stiffness fct of shear strain
  - UPC :
    - Advanced Hyperbolic Mohr-Coumb model
    - Nonlocal formulation
- **2 ≠ approaches**
  - But good agreement with the observations

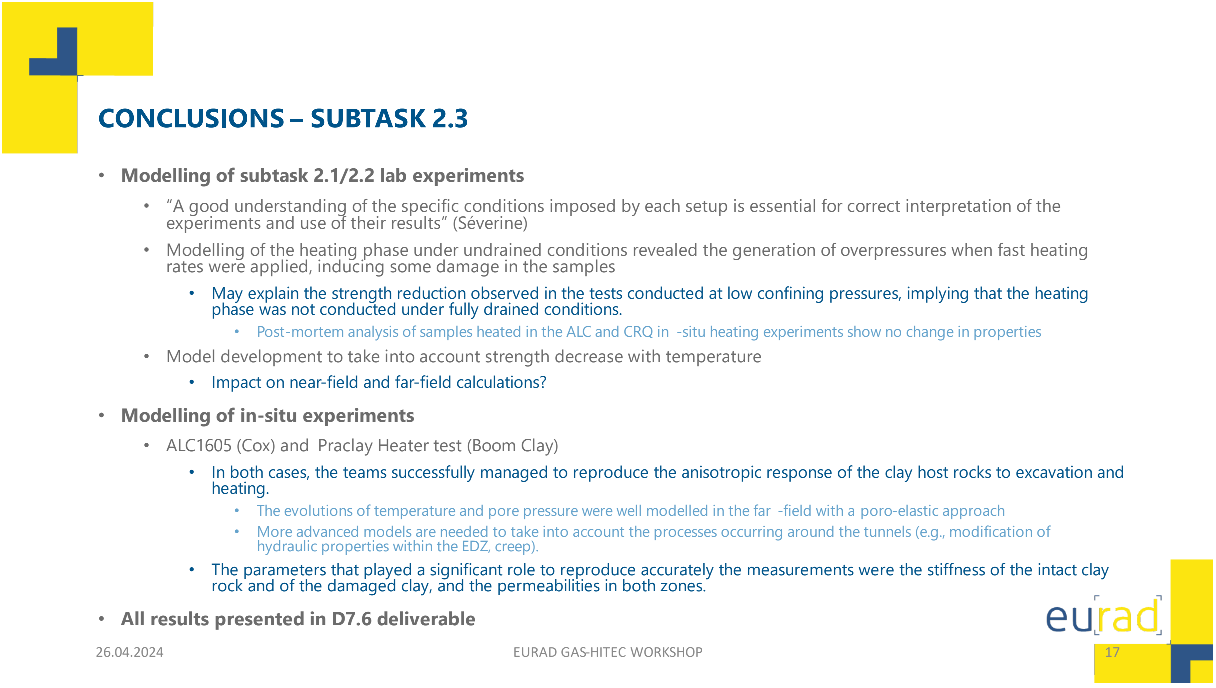
ULiège

UPC



CONCLUSIONS – SUBTASK 2.3

- **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
    - Variations on extent of EDZ, but effect of heating limited to very near field
- **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
  - Anisotropic poro-elastic behaviour known to provide a good prediction of the evolution of both T and PP (Seyedi et al., 2020)
  - Consistent results at mid-distance between two microtunnels
    - Builds confidence in this type of model
    - Confirms the robustness of the modelling approach used to dimension the Cigéo repository



CONCLUSIONS – SUBTASK 2.3

- **Modelling of subtask 2.1/2.2 lab experiments**
  - "A good understanding of the specific conditions imposed by each setup is essential for correct interpretation of the experiments and use of their results" (Séverine)
  - 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 ALC and CRQ in -situ heating experiments show no change in properties
  - Model development to take into account strength decrease with temperature
    - Impact on near-field and far-field calculations?
- **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 results presented in D7.6 deliverable**

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ACKNOWLEDGEMENTS

- **Thanks to the subtask 2.3 modellers:**
  - Minh-Ngoc Vu (Andra), Carlos Plua (Andra), Eric Simo (BGE), Alexandru Tatomir (BGE), Paola Léon Vargas (BGE), Pierre Bésuelle (CNRS-UGrenoble), Stefano Dal Pont (CNRS-UGrenoble), Alice di Donna (CNRS-UGrenoble), Nicolás Zalamea (CNRS-UGrenoble), Simon Raude (EDF), Ginger El Tabbal (EDF), Arnaud Dizier (EURIDICE), Mountaka Souley (Ineris), Asta Narkuniene (LEI), Gintautas Poskas (LEI), Povilas Poskas (LEI), Suresh Seetharam (SCK CEN), Frédéric Collin (ULiège), Hangbiao Song (ULiège), Abhishek Rawat (ULiège), Antonio Gens (UPC), Fei Song (UPC)

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MAIN MECHANICAL PROPERTIES FOR THE THREE CLAY FORMATIONS

- **Isotropic case:**

		BC	Cox	OPA
Solid phase density [kg/m³]	ρ_s	2639	2690	2340
Bulk density [kg/m³]	ρ'	2000	2386	2030
Porosity	n	0.39	0.18	0.13
Isotropic intrinsic permeability [m²]	K	$2.83E^{-19}$	$2.3E^{-20}$	$3.0E^{-20}$
Isotropic Young's modulus [MPa]	E	300	7000	6000
Poisson's ratio [-]	n	0.125	0.3	0.3
Biot coefficient		1	0.8	0.6
Isotropic thermal conductivity [W/m/K]	λ	1.47	1.67	1.85
Linear thermal expansion coefficient [K⁻¹]	α_s	$1E^{-5}$	$1.25E^{-5}$	$1.7E^{-5}$
Solid phase specific heat [J/kg/K]	c_p	769	790	995

- **Anisotropic case:**

		BC	Cox	OPA
Intrinsic permeability parallel to bedding [m²]	$k_{//}$	$4E^{-19}$	$3.9E^{-20}$	$5E^{-20}$
Intrinsic permeability normal to bedding [m²]	$k_{\perp}$	$2E^{-19}$	$1.3E^{-20}$	$1E^{-20}$
Young's modulus parallel to bedding [MPa]	$E_{//}$	400	8000	8000
Young's modulus normal to bedding [MPa]	$E_{\perp}$	200	5000	4000
Poisson's ratio parallel to bedding [-]	$\nu_{// //}$	0.125	0.2	0.35
Poisson's ratio normal to bedding [-]	$\nu_{\perp //}$	0.25	0.3	0.25
Shear modulus normal to bedding [MPa]	$G_{\perp}$	80	2500	2300
Thermal conductivity parallel to bedding [W/m/K]	$\lambda_{//}$	1.65	1.88	2.4
Thermal conductivity normal to bedding [W/m/K]	$\lambda_{\perp}$	1.31	1.25	1.3

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MAIN RESULTS – NEAR-FIELD (3/3)

- **Step 1.3 – Modelling of the Excavation Damaged Zone (EDZ)**
  - ULg:

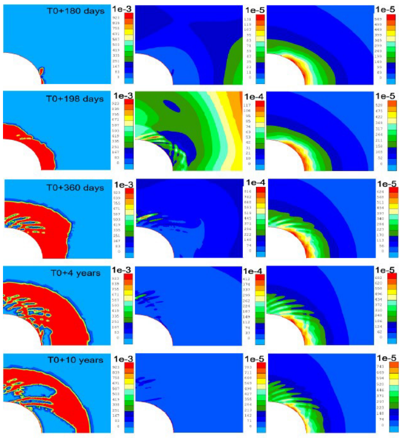

Figure 5.31: Evolution of plastic points, deviatoric strain increment and total deviatoric strain around the EDZ

UPC:

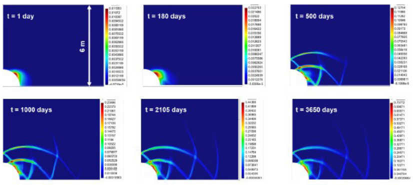

Figure 5.35: Evolution of the plastic shear strains, for the plastic anisotropic case Cox. Unsupported tunnel.

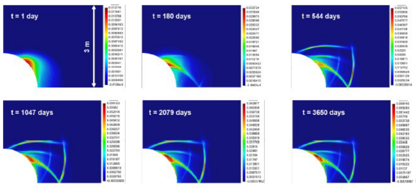

Figure 5.38: Evolution of the plastic shear strains, for the supported tunnel in the plastic anisotropic Cox case.

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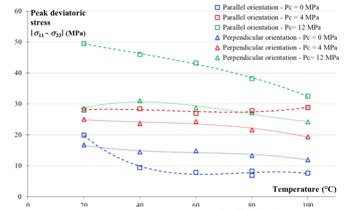
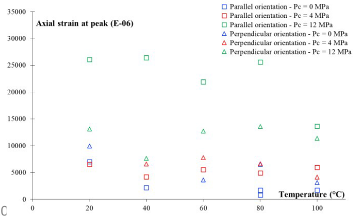
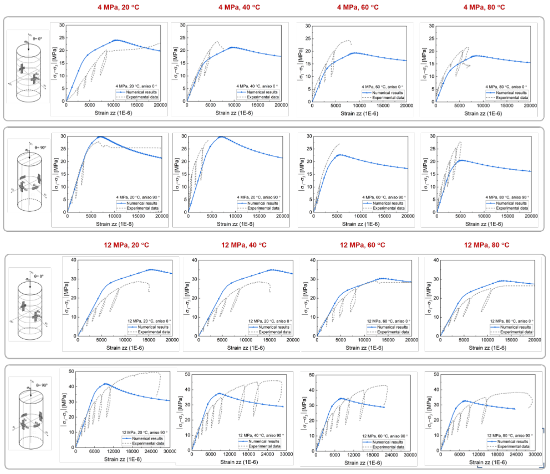
MODELLING OF LAB EXPERIMENTS

- **Strains in 12 MPa tests : // vs. ⊥ orientation**
    - Something wrong with core #EST66723 ?







Song et al., 2024

Session 2: Gas

2.1 Introduction: the GAS work package (EURAD-GAS)

eurad
European Joint Programme on Radioactive Waste Management

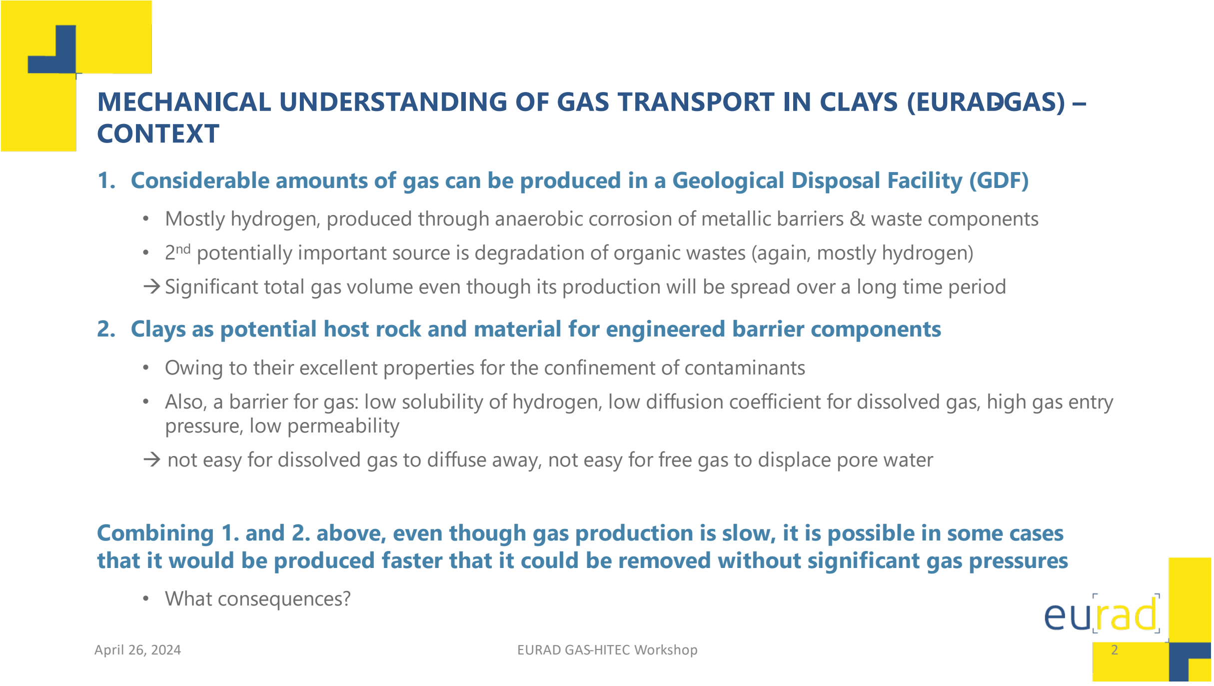
GENERAL OVERVIEW OF EURAD-GAS

EURAD GAS-HITEC Workshop

26 April 2024 • Séverine Levasseur

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°847593

April 26, 2024 EURAD GAS-HITEC Workshop 1



MECHANICAL UNDERSTANDING OF GAS TRANSPORT IN CLAYS (EURAD-GAS) – CONTEXT

1. **Considerable amounts of gas can be produced in a Geological Disposal Facility (GDF)**
   - Mostly hydrogen, produced through anaerobic corrosion of metallic barriers & waste components
   - 2nd potentially important source is degradation of organic wastes (again, mostly hydrogen)

   → Significant total gas volume even though its production will be spread over a long time period
2. **Clays as potential host rock and material for engineered barrier components**
   - Owing to their excellent properties for the confinement of contaminants
   - Also, a barrier for gas: low solubility of hydrogen, low diffusion coefficient for dissolved gas, high gas entry pressure, low permeability

   → not easy for dissolved gas to diffuse away, not easy for free gas to displace pore water

Combining 1. and 2. above, even though gas production is slow, it is possible in some cases that it would be produced faster that it could be removed without significant gas pressures

- What consequences?

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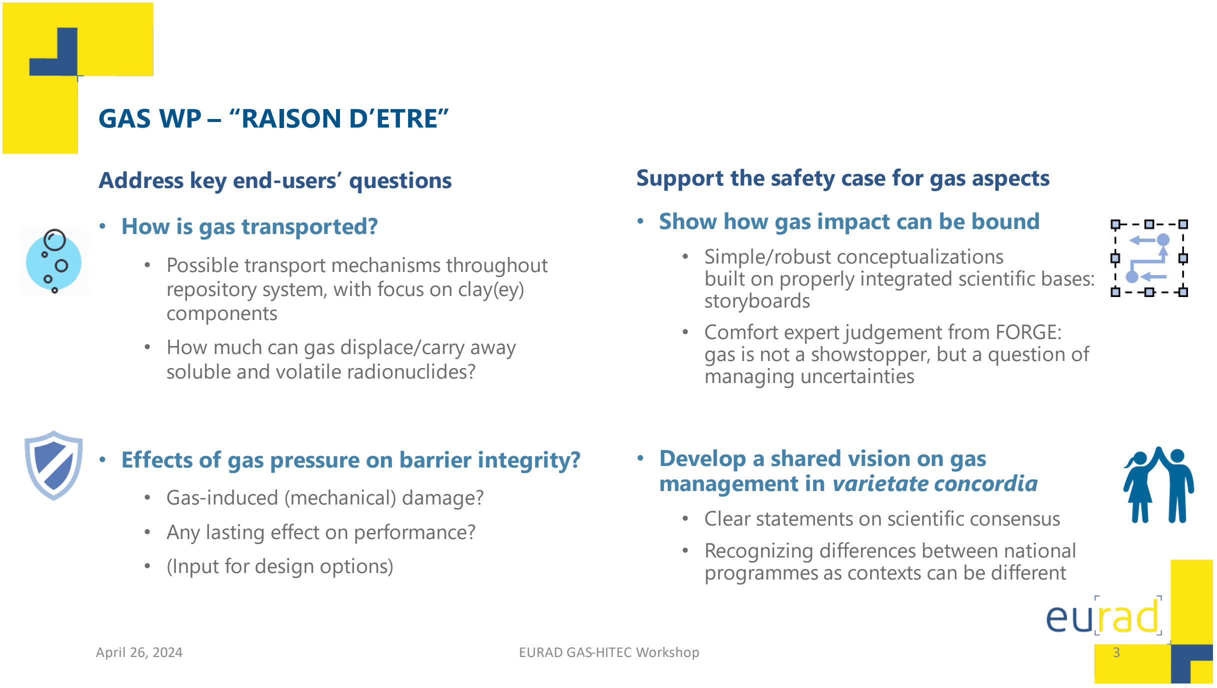
April 26, 2024 EURAD GAS-HITEC Workshop 2



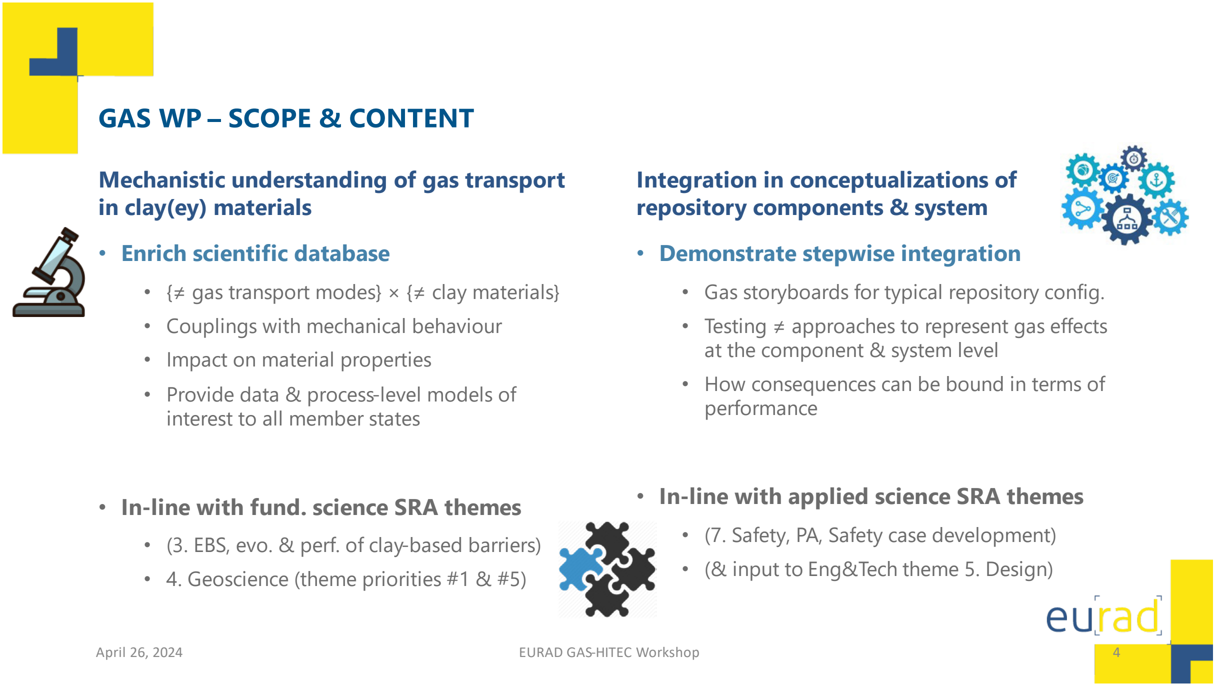
GAS WP – "RAISON D'ETRE"

Address key end-users' questions

- **How is gas transported?**
  - Possible transport mechanisms throughout repository system, with focus on clay(ey) components
  - How much can gas displace/carry away soluble and volatile radionuclides?
- **Effects of gas pressure on barrier integrity?**
  - Gas-induced (mechanical) damage?
  - Any lasting effect on performance?
  - (Input for design options)

Support the safety case for gas aspects

- **Show how gas impact can be bound**
  - Simple/robust conceptualizations built on properly integrated scientific bases: storyboards
  - Comfort expert judgement from FORGE: gas is not a showstopper, but a question of managing uncertainties
- **Develop a shared vision on gas management in *varietate concordia***
  - Clear statements on scientific consensus
  - Recognizing differences between national programmes as contexts can be different



GAS WP – SCOPE & CONTENT

Mechanistic understanding of gas transport in clay(ey) materials

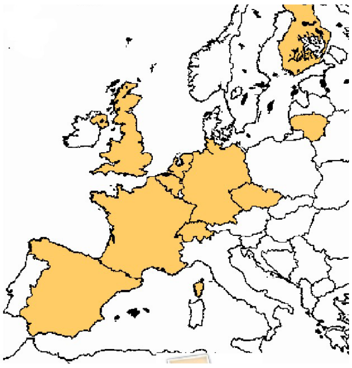
- **Enrich scientific database**
  - {≠ gas transport modes} × {≠ clay materials}
  - Couplings with mechanical behaviour
  - Impact on material properties
  - Provide data & process-level models of interest to all member states
- **In-line with fund. science SRA themes**
  - (3. EBS, evo. & perf. of clay-based barriers)
  - 4. Geoscience (theme priorities #1 & #5)

Integration in conceptualizations of repository components & system

- **Demonstrate stepwise integration**
  - Gas storyboards for typical repository config.
  - Testing ≠ approaches to represent gas effects at the component & system level
  - How consequences can be bound in terms of performance
- **In-line with applied science SRA themes**
  - (7. Safety, PA, Safety case development)
  - (& input to Eng&Tech theme 5. Design)

GAS WP – PARTICIPANTS

29 organizations from 10 countries



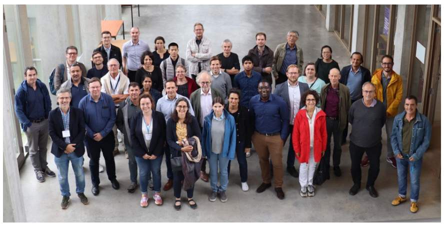
Organisations

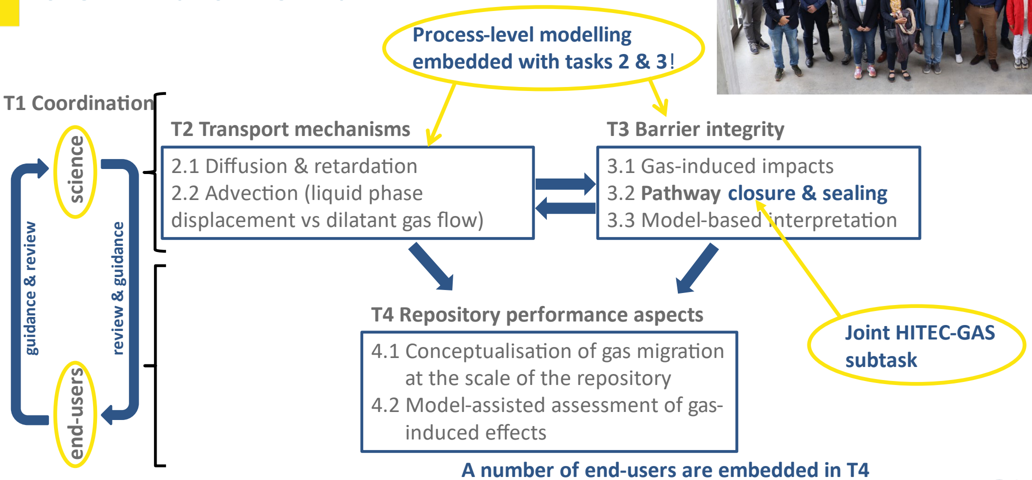
- ✓ **SCK-CEN** (BE, RE)
- ✓ **ONDRAF/NIRAS** (BE, WMO)
  - **ULiège** (BE, RE)
- ✓ **PSI** (CH, RE)
- ✓ **NAGRA** (CH, WMO)
  - **EPFL** (CH, RE)
  - **ZHAW** (CH, RE)
  - **CIMNE** (ES, RE)
- ✓ **SÚRAO** (CZ,WMO)
  - **CTU** (CZ, RE)
  - **UJV** (CZ, RE)
- ✓ FZJ
  - **UFZ** (DE, RE)
- ✓ KIT-PTKA
  - **GRS** (DE, RE)
  - **BGR** (DE, RE)
- ✓ **BGE** (DE, WMO)
- ✓ **CIEMAT** (ES, TSO)
  - **UPC** (ES, RE)

Organisations

- ✓ University of Helsinki
  - **Aalto Uni** (FI, RE)
- ✓ CNRS (RE, FR)
  - CNRS / **ISTerre**
  - CNRS / **GeoRess**.
  - CNRS / **IC2MP**
- ✓ **IRSN** (FR, TSO)
- ✓ **Andra** (FR, WMO)
- ✓ CEA
  - **EDF** (FR, RE)
- ✓ **LEI** (LT, RE)
- ✓ **COVRA** (NL, WMO)
  - **TU Delft** (NL, RE)
- ✓ **BGS** (UK, RE)
- ✓ **RWM** (UK, WMO)

GAS WP – ORGANISATION





Process-level modelling embedded with tasks 2 & 3!

T1 Coordination

T2 Transport mechanisms

2.1 Diffusion & retardation
2.2 Advection (liquid phase displacement vs dilatant gas flow)

T3 Barrier integrity

3.1 Gas-induced impacts
3.2 **Pathway closure & sealing**
3.3 Model-based interpretation

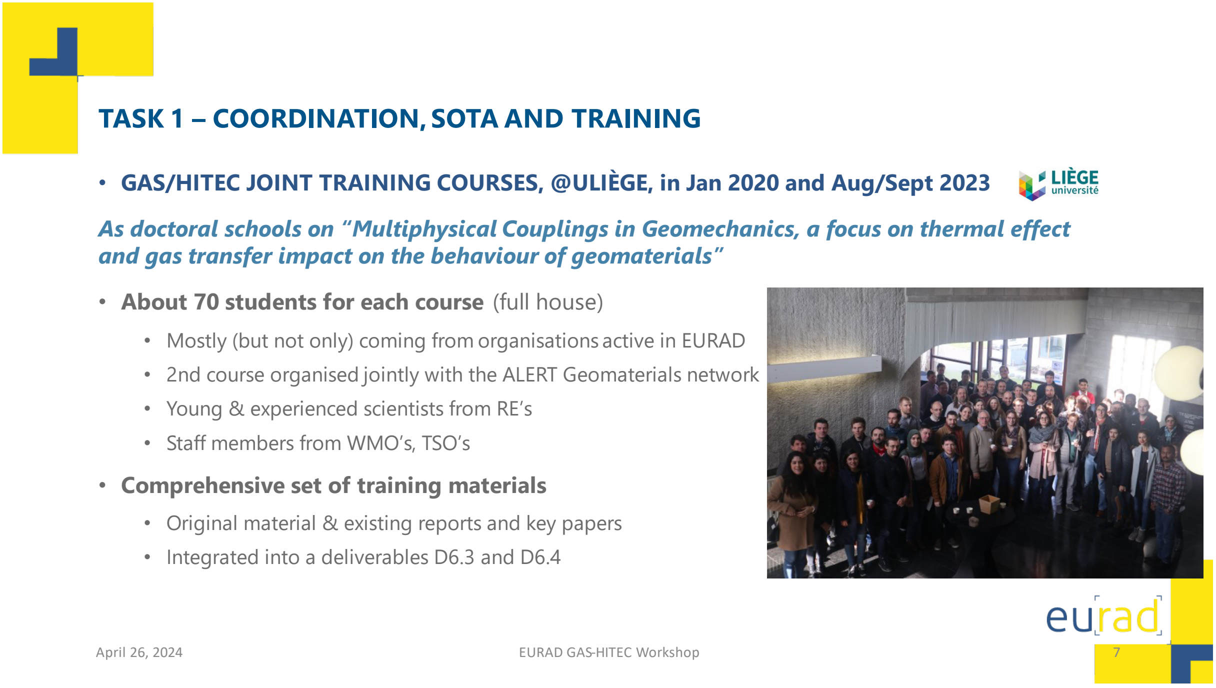
Joint HITEC-GAS subtask

T4 Repository performance aspects

4.1 Conceptualisation of gas migration at the scale of the repository
4.2 Model-assisted assessment of gas-induced effects

A number of end-users are embedded in T4

+ Liaise with KM SoC, guidance & training



TASK 1 – COORDINATION, SOTA AND TRAINING

- **GAS/HITEC JOINT TRAINING COURSES, @ULIÈGE, in Jan 2020 and Aug/Sept 2023**

As doctoral schools on "Multiphysical Couplings in Geomechanics, a focus on thermal effect and gas transfer impact on the behaviour of geomaterials"

- **About 70 students for each course** (full house)
  - Mostly (but not only) coming from organisations active in EURAD
  - 2nd course organised jointly with the ALERT Geomaterials network
  - Young & experienced scientists from RE's
  - Staff members from WMO's, TSO's
- **Comprehensive set of training materials**
  - Original material & existing reports and key papers
  - Integrated into a deliverables D6.3 and D6.4

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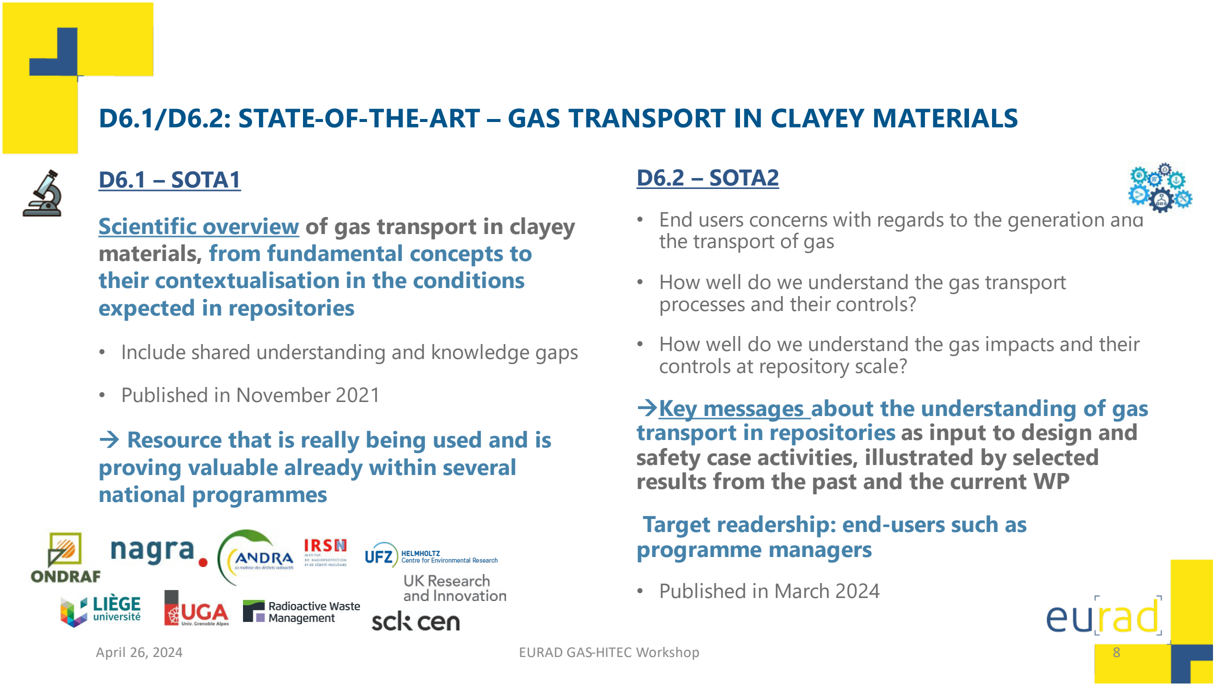

D6.1/D6.2: STATE-OF-THE-ART – GAS TRANSPORT IN CLAYEY MATERIALS

D6.1 – SOTA1

Scientific overview of gas transport in clayey materials, from fundamental concepts to their contextualisation in the conditions expected in repositories

- Include shared understanding and knowledge gaps
- Published in November 2021

→ Resource that is really being used and is proving valuable already within several national programmes

D6.2 – SOTA2

- End users concerns with regards to the generation and the transport of gas
- How well do we understand the gas transport processes and their controls?
- How well do we understand the gas impacts and their controls at repository scale?

→Key messages about the understanding of gas transport in repositories as input to design and safety case activities, illustrated by selected results from the past and the current WP

Target readership: end-users such as programme managers

- Published in March 2024

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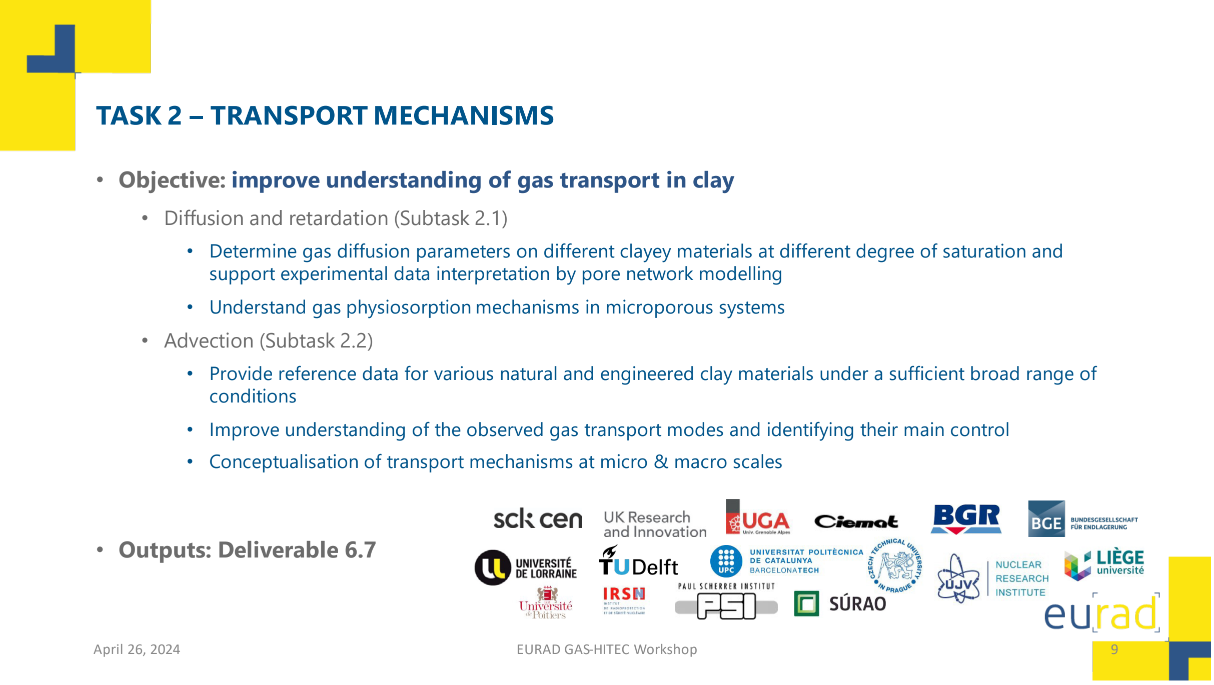
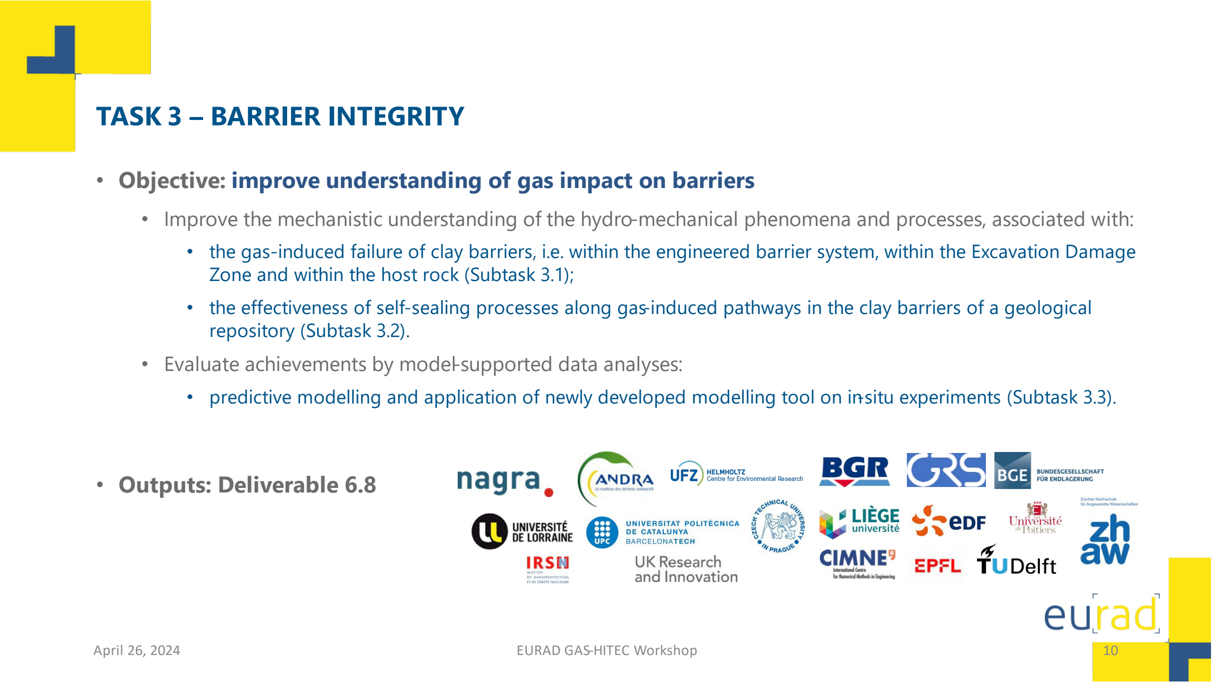


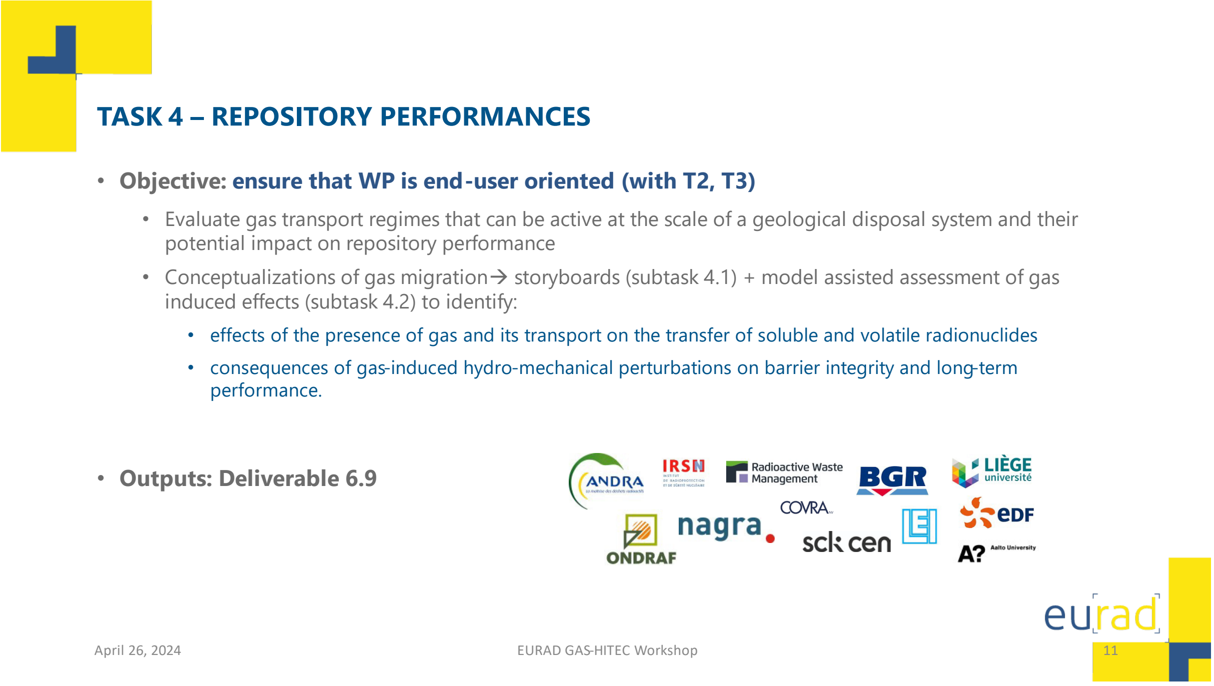
TASK 2 – TRANSPORT MECHANISMS

- **Objective: improve understanding of gas transport in clay**
  - Diffusion and retardation (Subtask 2.1)
    - Determine gas diffusion parameters on different clayey materials at different degree of saturation and support experimental data interpretation by pore network modelling
    - Understand gas physiosorption mechanisms in microporous systems
  - Advection (Subtask 2.2)
    - Provide reference data for various natural and engineered clay materials under a sufficient broad range of conditions
    - Improve understanding of the observed gas transport modes and identifying their main control
    - Conceptualisation of transport mechanisms at micro & macro scales
- **Outputs: Deliverable 6.7**



TASK 3 – BARRIER INTEGRITY

- **Objective: improve understanding of gas impact on barriers**
  - Improve the mechanistic understanding of the hydro-mechanical phenomena and processes, associated with:
    - the gas-induced failure of clay barriers, i.e. within the engineered barrier system, within the Excavation Damage Zone and within the host rock (Subtask 3.1);
    - the effectiveness of self-sealing processes along gas-induced pathways in the clay barriers of a geological repository (Subtask 3.2).
  - Evaluate achievements by model-supported data analyses:
    - predictive modelling and application of newly developed modelling tool on in-situ experiments (Subtask 3.3).
- **Outputs: Deliverable 6.8**



TASK 4 – REPOSITORY PERFORMANCES

- **Objective: ensure that WP is end-user oriented (with T2, T3)**
  - Evaluate gas transport regimes that can be active at the scale of a geological disposal system and their potential impact on repository performance
  - Conceptualizations of gas migration→ storyboards (subtask 4.1) + model assisted assessment of gas induced effects (subtask 4.2) to identify:
    - effects of the presence of gas and its transport on the transfer of soluble and volatile radionuclides
    - consequences of gas-induced hydro-mechanical perturbations on barrier integrity and long-term performance.
- **Outputs: Deliverable 6.9**

April 26, 2024 EURAD GAS-HITEC Workshop 11

EURAD GAS-HITEC WORKSHOP → ACHIEVEMENTS OF EURAD-GAS

- **Advances within EURAD in knowledge on gas transport issues (morning Session)**
  - Diffusive transport by E. Jacops
  - Advective transport by L. Gonzalez-Blanco
  - → In line with Task 2 and Task 3 results

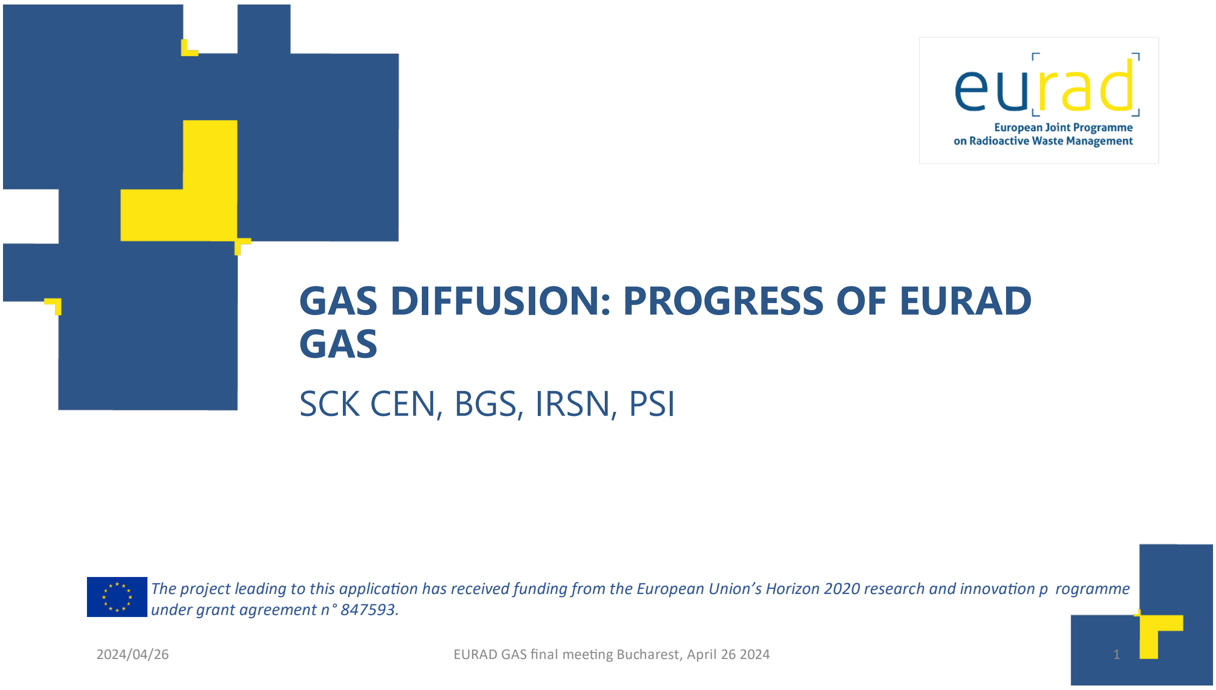
- **Input to the repository design and the safety case**

→ how the results of EURAD-GAS can be used by end-users (afternoon session)

- Key messages for the treatment of gas transport by J. Wendling and P. Marschall
- → In line with Task 4 results

April 26, 2024 EURAD GAS-HITEC Workshop 12

2.2 Key results on gas diffusion



GAS DIFFUSION: PROGRESS OF EURAD GAS

SCK CEN, BGS, IRSN, PSI

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation p rogramme under grant agreement n° 847593.

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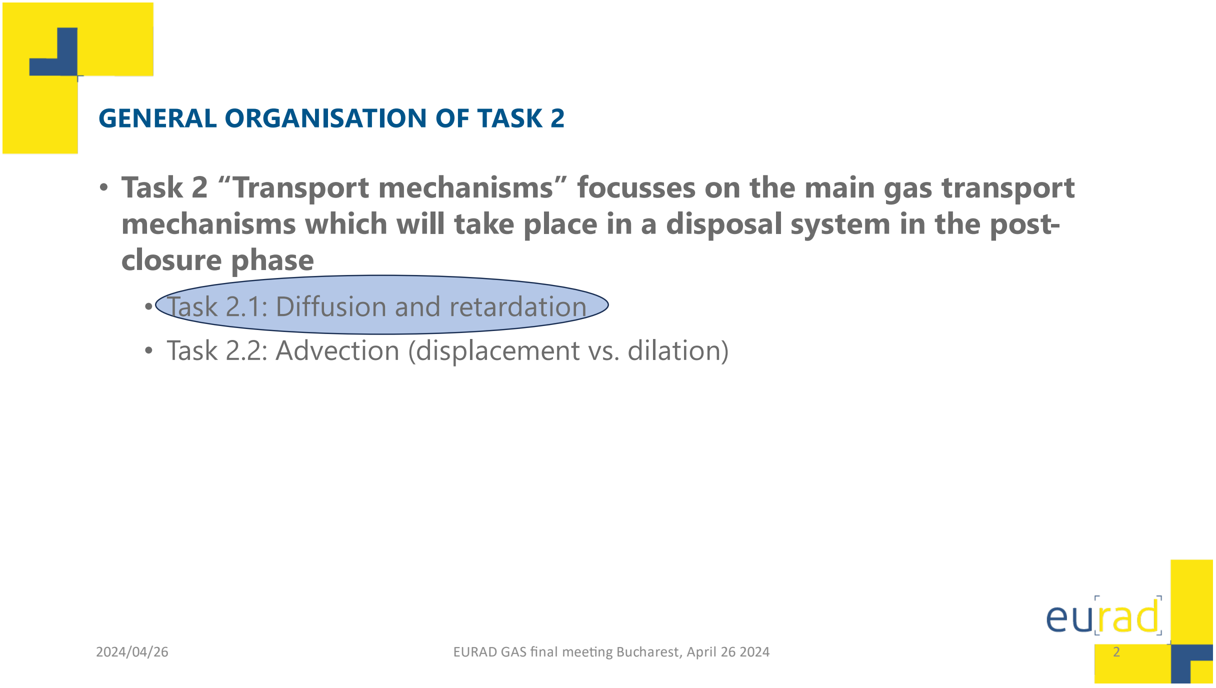

GENERAL ORGANISATION OF TASK 2

- **Task 2 "Transport mechanisms" focusses on the main gas transport mechanisms which will take place in a disposal system in the post-closure phase**
  - Task 2.1: Diffusion and retardation
  - Task 2.2: Advection (displacement vs. dilation)

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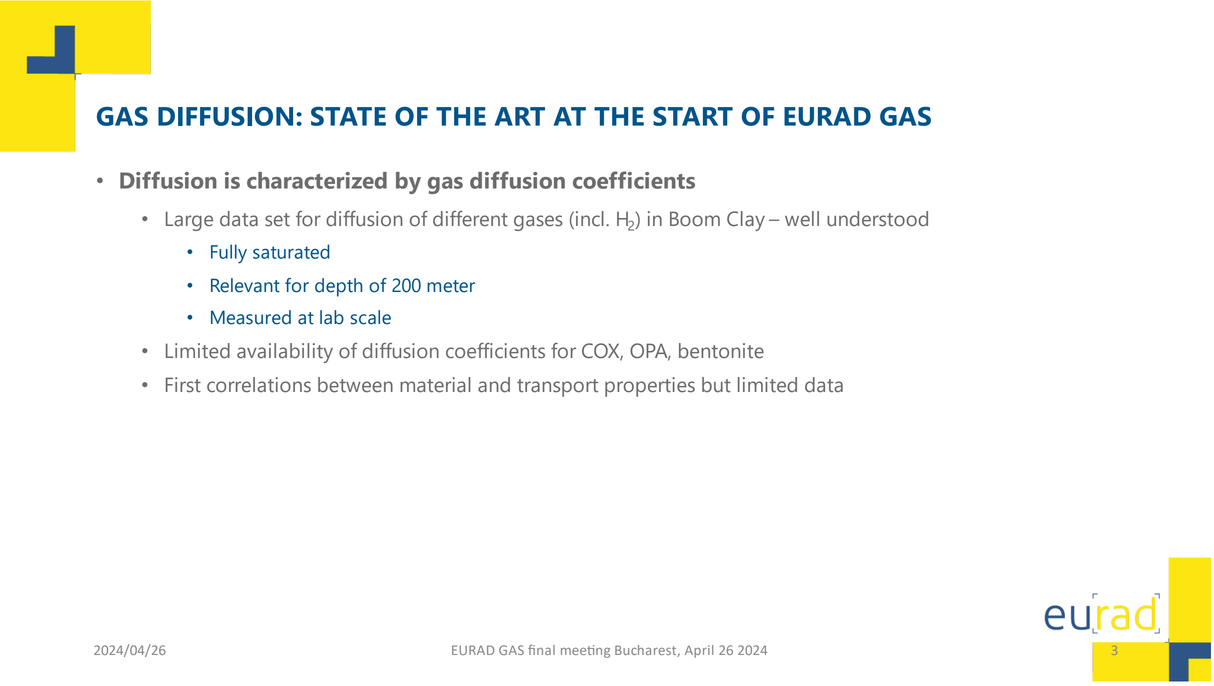
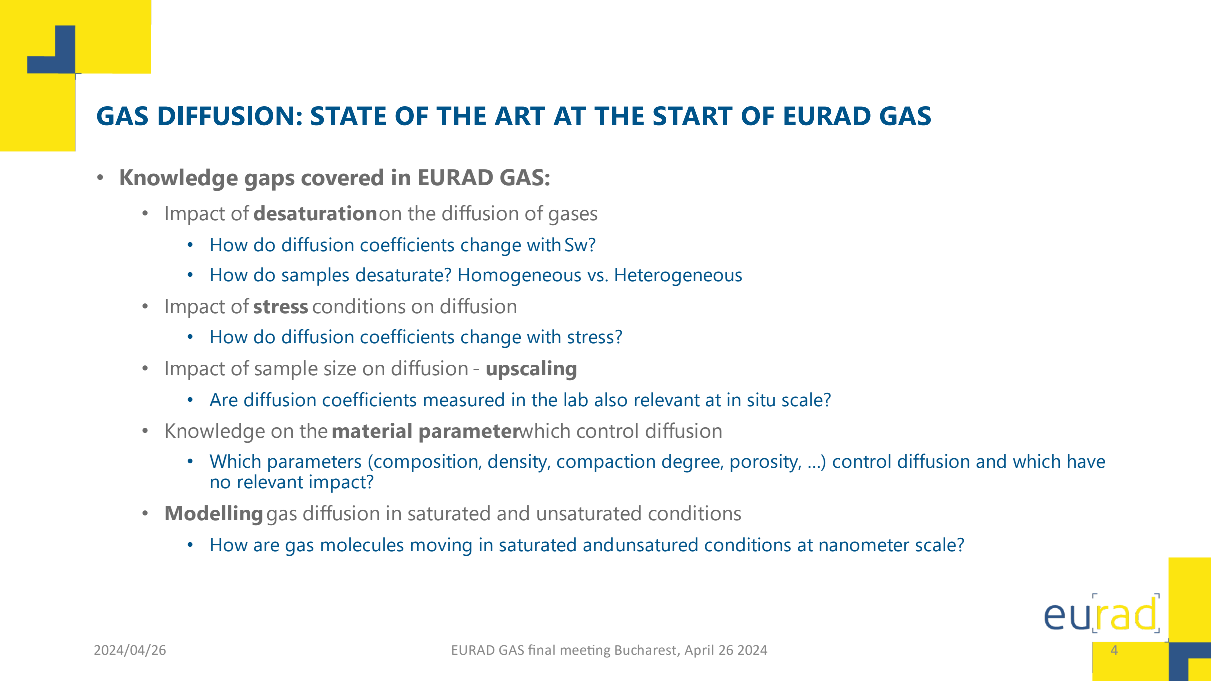


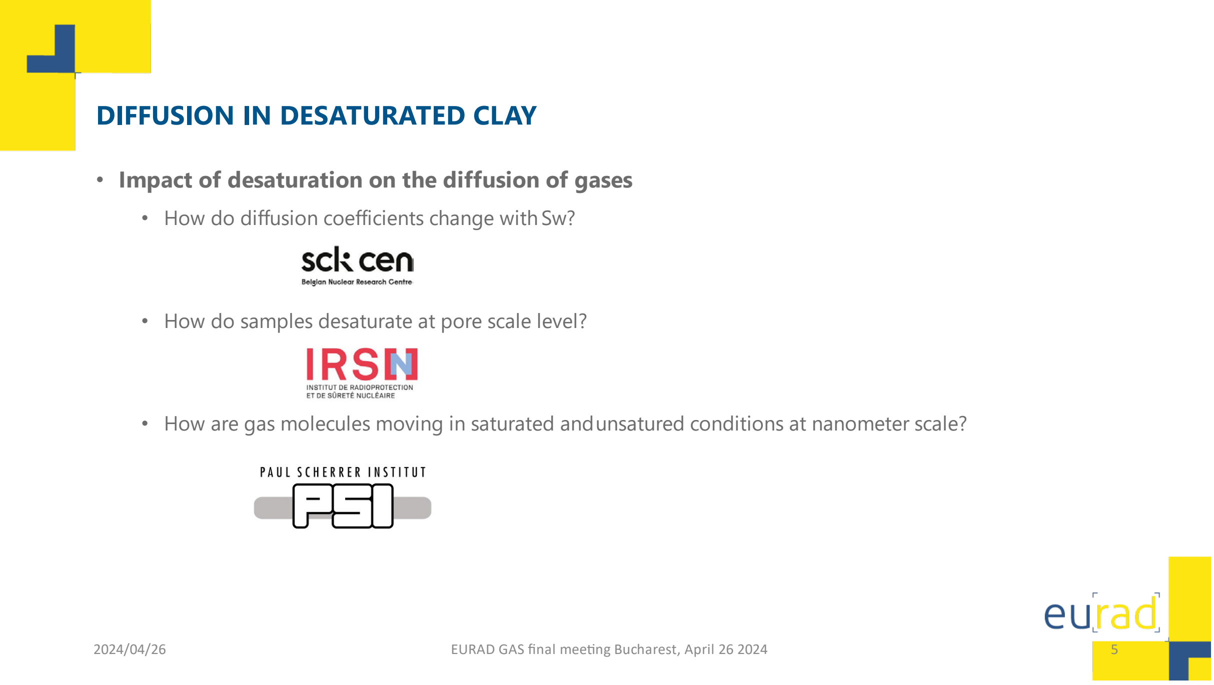
GAS DIFFUSION: STATE OF THE ART AT THE START OF EURAD GAS

- **Diffusion is characterized by gas diffusion coefficients**
  - Large data set for diffusion of different gases (incl. H_2) in Boom Clay – well understood
    - Fully saturated
    - Relevant for depth of 200 meter
    - Measured at lab scale
  - Limited availability of diffusion coefficients for COX, OPA, bentonite
  - First correlations between material and transport properties but limited data



GAS DIFFUSION: STATE OF THE ART AT THE START OF EURAD GAS

- **Knowledge gaps covered in EURAD GAS:**
  - Impact of **desaturation** on the diffusion of gases
    - How do diffusion coefficients change with Sw?
    - How do samples desaturate? Homogeneous vs. Heterogeneous
  - Impact of **stress** conditions on diffusion
    - How do diffusion coefficients change with stress?
  - Impact of sample size on diffusion - **upscaling**
    - Are diffusion coefficients measured in the lab also relevant at in situ scale?
  - Knowledge on the **material parameter** which control diffusion
    - Which parameters (composition, density, compaction degree, porosity, …) control diffusion and which have no relevant impact?
  - **Modelling** gas diffusion in saturated and unsaturated conditions
    - How are gas molecules moving in saturated and unsatured conditions at nanometer scale?



DIFFUSION IN DESATURATED CLAY

- **Impact of desaturation on the diffusion of gases**
  - How do diffusion coefficients change with Sw?

    sck cen Belgian Nuclear Research Centre
  - How do samples desaturate at pore scale level?

    IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE
  - How are gas molecules moving in saturated and unsatured conditions at nanometer scale?

    PAUL SCHERRER INSTITUT PSI

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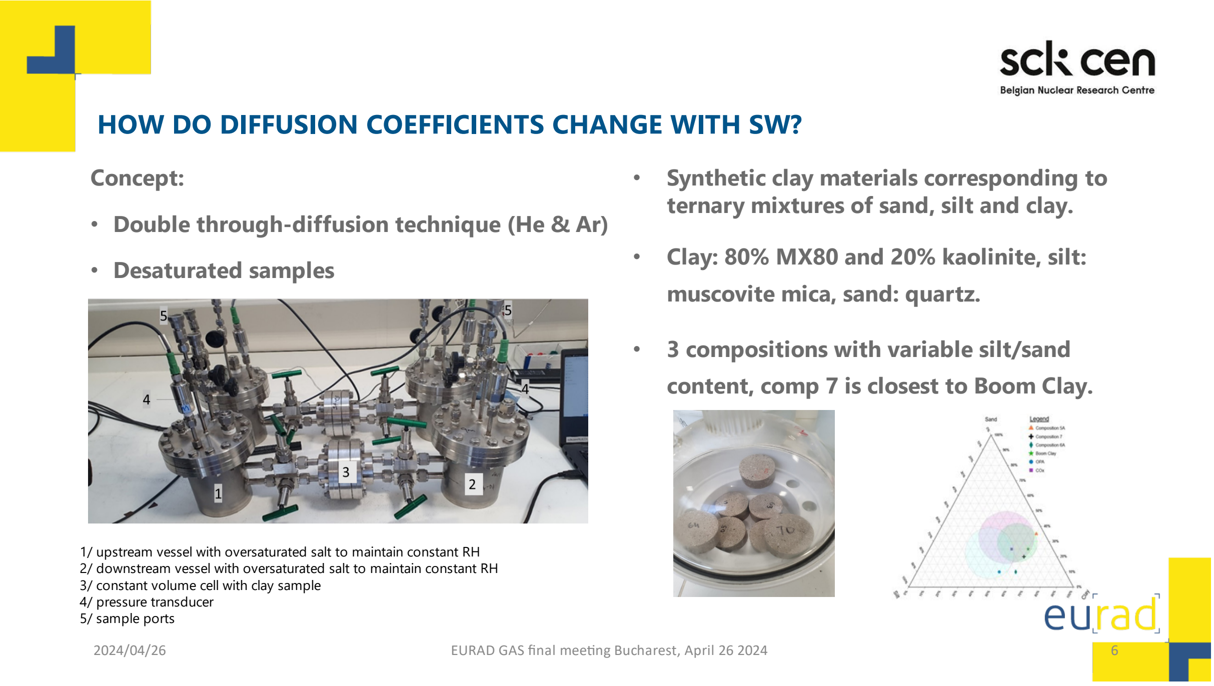

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HOW DO DIFFUSION COEFFICIENTS CHANGE WITH SW?

Concept:

- **Double through-diffusion technique (He & Ar)**
- **Desaturated samples**

1/ upstream vessel with oversaturated salt to maintain constant RH
2/ downstream vessel with oversaturated salt to maintain constant RH
3/ constant volume cell with clay sample
4/ pressure transducer
5/ sample ports

- **Synthetic clay materials corresponding to ternary mixtures of sand, silt and clay.**
- **Clay: 80% MX80 and 20% kaolinite, silt: muscovite mica, sand: quartz.**
- **3 compositions with variable silt/sand content, comp 7 is closest to Boom Clay.**

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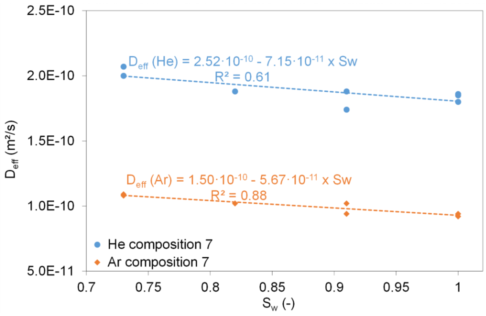
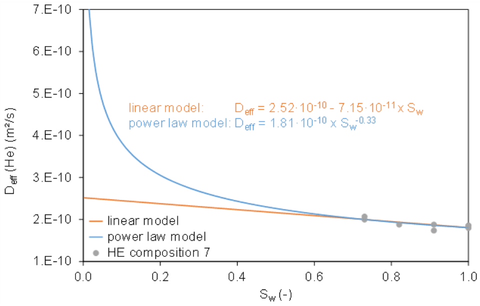
HOW DO DIFFUSION COEFFICIENTS CHANGE WITHSW?





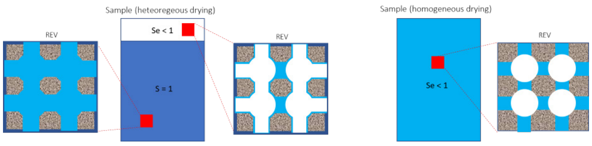
- **Diffusivity slightly increases with desaturation.**
- **In high saturation range (70 – 100%), evolution can be described with linear relation.**

- **Alternatively, a power law (based on Archie’s law) could be used, but this needs data < 40% Sw (cfr. Savoye et al., 2010).**

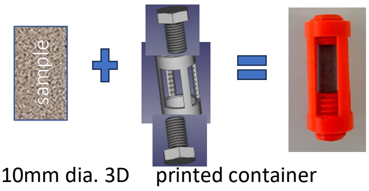
Savoye, S., J. Page, C. Puente, C. Imbert and D. Coelho (2010). "New Experimental Approach for Studying Diffusion through an Intact and Unsaturated Medium: A Case Study with Callovo-Oxfordian Argillite." Environmental Science & Technology 44(10): 3698-3704.

HOW DO SAMPLES DESATURATE?

- **Homogeneous or heterogeneous ?**

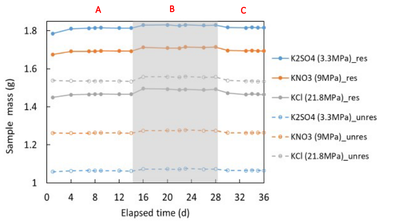


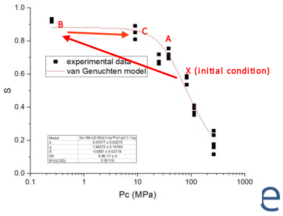
- **Toarcian and Eigenbilzen sand samples**

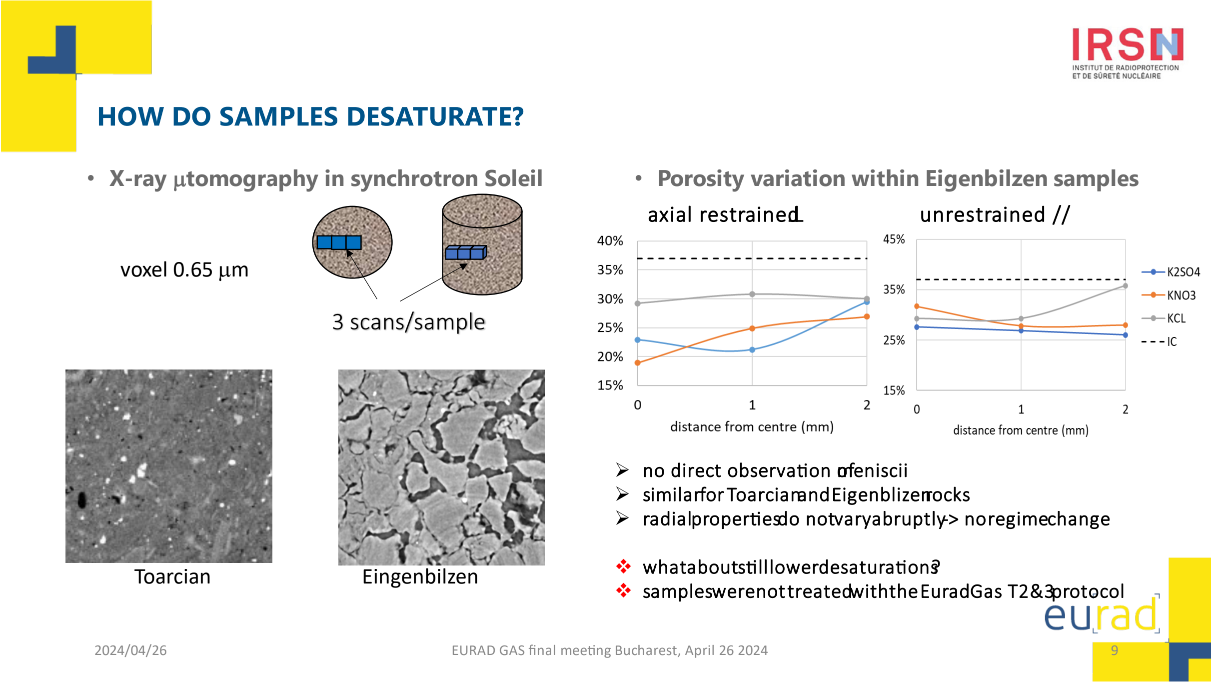


7-10mm dia. 3D printed container

- **Equilibration at different relative humidity**







HOW DO SAMPLES DESATURATE?

- X-ray µtomography in synchrotron Soleil
- Porosity variation within Eigenbilzen samples

voxel 0.65 µm

3 scans/sample

Toarcian

Eingenbilzen

- ➢ no direct observation of meniscii
- ➢ similar for Toarcian and Eigenblizen rocks
- ➢ radial properties do not vary abruptly -> no regime change

- ❖ what about still lower desaturations?
- ❖ samples were not treated with the EuradGas T2&3 protocol

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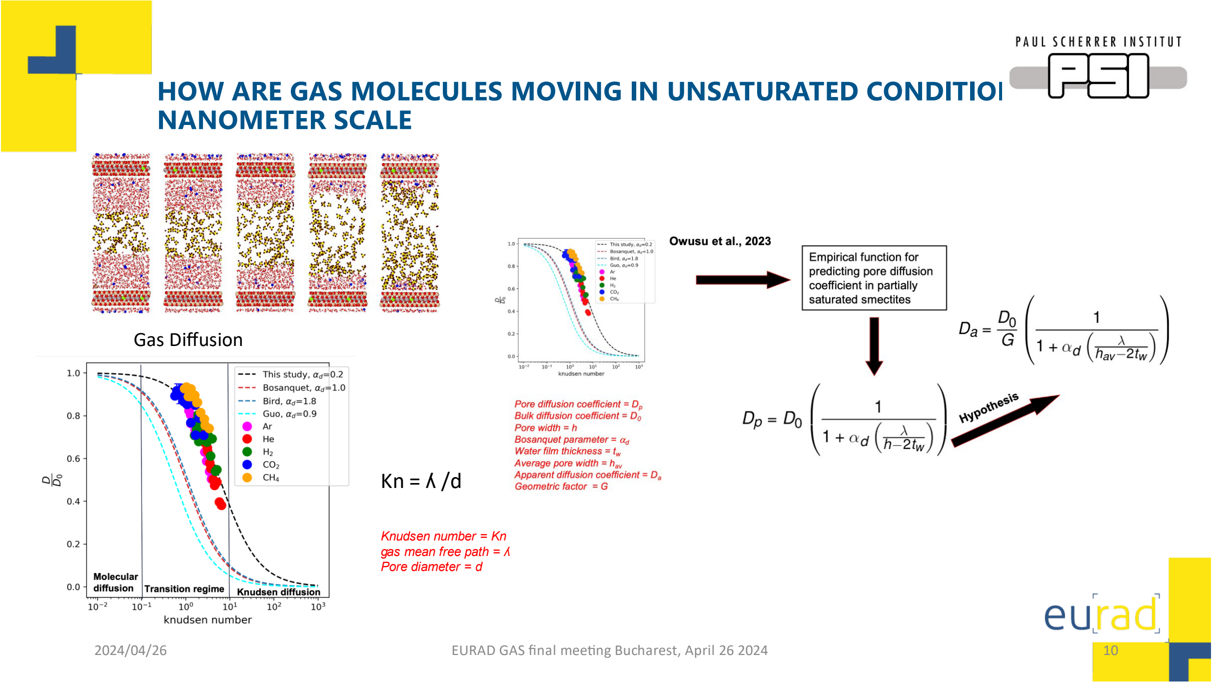

HOW ARE GAS MOLECULES MOVING IN UNSATURATED CONDITIOI NANOMETER SCALE

Gas Diffusion

Kn = ʎ /d

Knudsen number = Kn
gas mean free path = ʎ
Pore diameter = d

Owusu et al., 2023

Pore diffusion coefficient = D_p
Bulk diffusion coefficient = D_0
Pore width = h
Bosanquet parameter = α_d
Water film thickness = t_w
Average pore width = h_{av}
Apparent diffusion coefficient = D_a
Geometric factor = G

Empirical function for predicting pore diffusion coefficient in partially saturated smectites

$$D_p = D_0\left(\frac{1}{1+\alpha_d\left(\frac{\lambda}{h-2t_w}\right)}\right)$$

Hypothesis

$$D_a = \frac{D_0}{G}\left(\frac{1}{1+\alpha_d\left(\frac{\lambda}{h_{av}-2t_w}\right)}\right)$$

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IMPACT OF STRESS AND MATERIAL PARAMETERS

- **Impact of stress conditions on diffusion**
  - How do diffusion coefficients change with stress?

British Geological Survey

- **Knowledge on the material parameters which control diffusion**
  - Which parameters (composition, density, compaction degree, porosity, …) control diffusion and which have no relevant impact?

British Geological Survey

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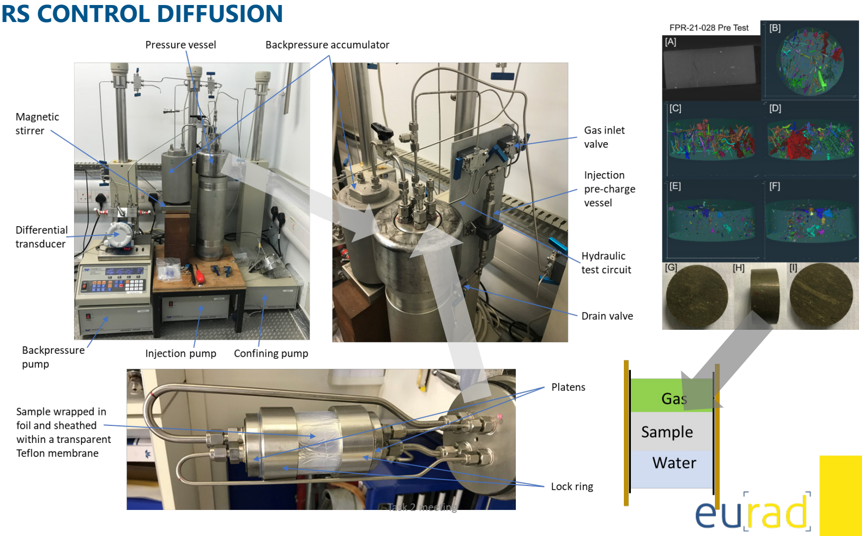
British Geological Survey

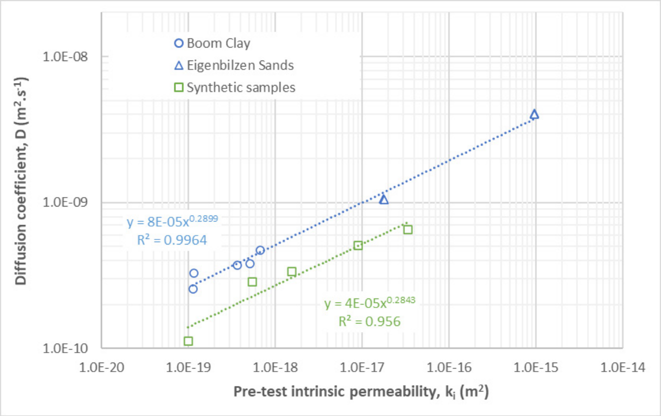
HOW DO DIFFUSION COEFFICIENTS CHANGE WITH BEDDING ANISOTROPY AND WHICH MATERIAL PARAMETERS CONTROL DIFFUSION

- **Apparatus: cylindrical samples are isotropically stressed at σ=8.0 MPa and p_w=3.9 MPa**
- **Samples are subjected to detailed pre- and post-test characterisation**
- **Tests comprise equilibration, hydraulic permeability, diffusion, and repeat hydraulic permeability stages**
- **Natural and synthetic materials tested**



HOW DO DIFFUSION COEFFICIENTS CHANGE WITH BEDDING ANISOTROPY ANDWHICH MATERIAL PARAMETERS CONTROL DIFFUSION

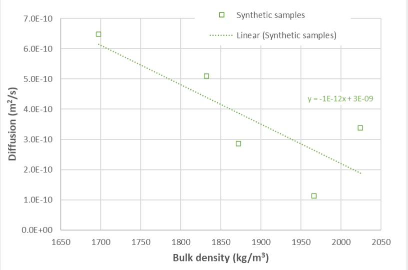
- While there's a paucity of data, permeability and diffusivity appear to be fundamentally linked
- Based on the limited information derived from this study, gas appears to preferentially diffuse parallel to bedding with nearly 60% of the diffusional capacity of the Boom Clay moving within the bedding planes
- Offset between natural and synthetic samples suggests compaction may have been too high – alludes to the importance of stress and burial history but shows the potential of synthetic samples to explore behaviours and trends



HOW DO DIFFUSION COEFFICIENTS CHANGE WITH BEDDING ANISOTROPY ANDWHICH MATERIAL PARAMETERS CONTROL DIFFUSION

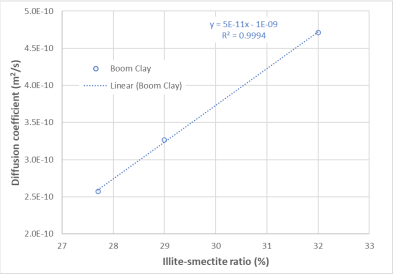
While data very limited we have started to explore some possible correlators….

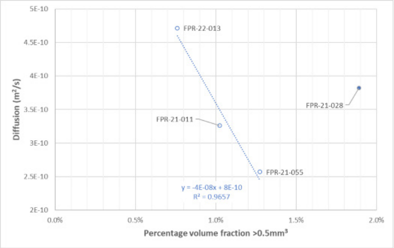
- Synesthetic sample data shows a crude coupling to bulk density suggesting mineralogy and burial history may impact diffusivity



Future: complete analysis, combine findings with SCK CEN data and look for systematic trends and commonalities (s ubmitted an abstract to Clay Barrier Meeting, Nov 2024). Data collection and collaboration will hopefully continue

- Data also alludes to a possible correlation between clay type….





- Diffusion may also be linked to fabric related features visible in CT scans, but more data and further analysis is required

MODELLING GAS DIFFUSION IN SATURATED AND UNSATURATED CONDITIONS

- **Modelling gas diffusion in saturated conditions**
  - How are gas molecules moving in saturated conditions at nanometer scale?

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HOW ARE GAS MOLECULES MOVING IN SATURATED CONDITIONS AT NANOMETER SCALE

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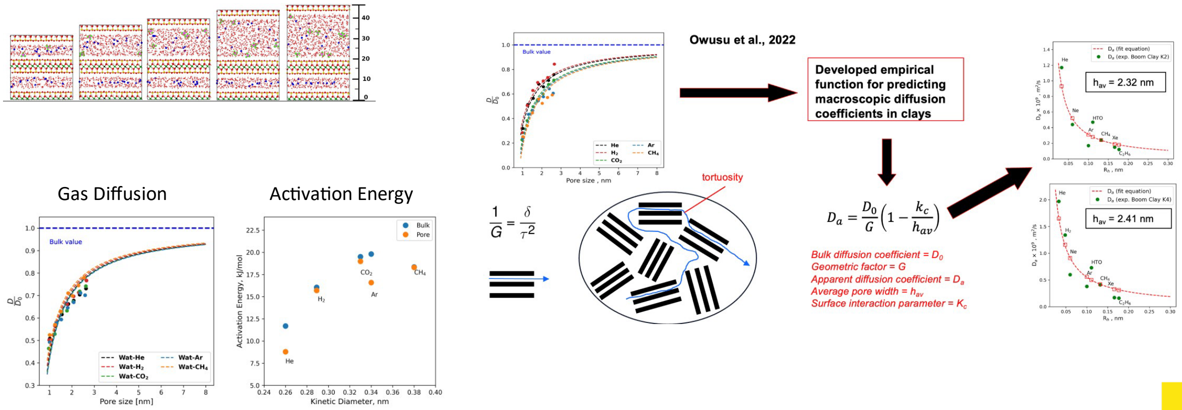

Owusu et al., 2022

Developed empirical function for predicting macroscopic diffusion coefficients in clays

$$\frac{1}{G} = \frac{\delta}{\tau^2}$$

$$D_a = \frac{D_0}{G}\left(1 - \frac{k_c}{h_{av}}\right)$$

Bulk diffusion coefficient = D_0
Geometric factor = G
Apparent diffusion coefficient = D_a
Average pore width = h_{av}
Surface interaction parameter = K_c

UPSCALING

- **Impact of sample size on diffusion**
  - Are diffusion coefficients measured in the lab also relevant at in situ scale?

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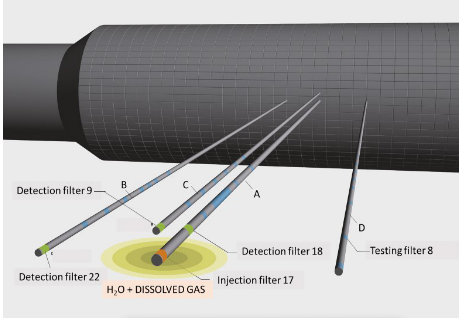
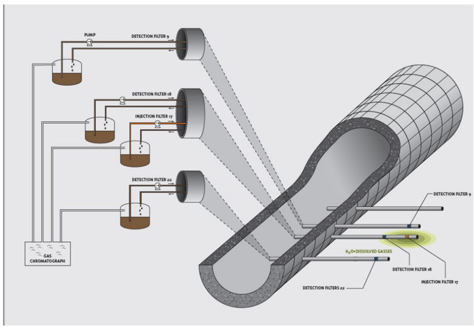
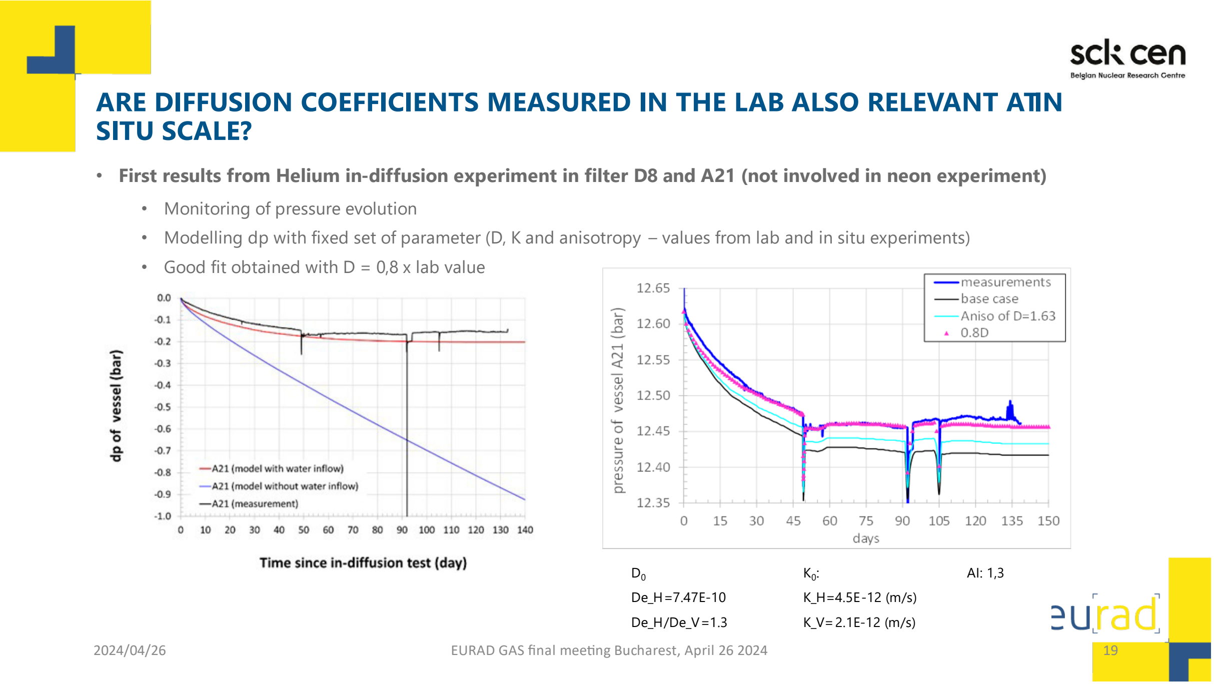
ARE DIFFUSION COEFFICIENTS MEASURED IN THE LAB ALSO RELEVANT AT IN SITU SCALE?

- **NEMESIS: Neon diffusion in MEgaS In Situ experiment**
  - through-diffusion experiment
  - Filter distance (30 cm to 1 meter) – 3D







ARE DIFFUSION COEFFICIENTS MEASURED IN THE LAB ALSO RELEVANT AT IN SITU SCALE?

- **First results from Helium in-diffusion experiment in filter D8 and A21 (not involved in neon experiment)**
  - Monitoring of pressure evolution
  - Modelling dp with fixed set of parameter (D, K and anisotropy – values from lab and in situ experiments)
  - Good fit obtained with D = 0,8 x lab value

D_0	K_0:	AI: 1,3
De_H=7.47E-10	K_H=4.5E-12 (m/s)	
De_H/De_V=1.3	K_V= 2.1E-12 (m/s)	

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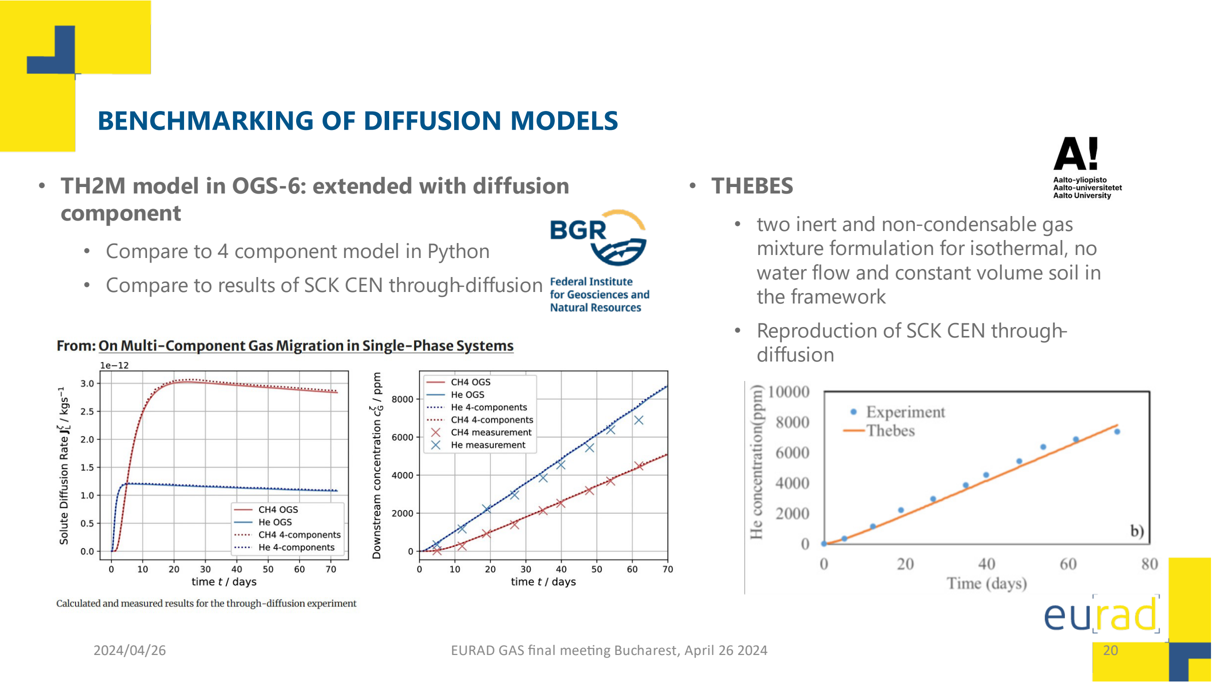

BENCHMARKING OF DIFFUSION MODELS

- **TH2M model in OGS-6: extended with diffusion component**
  - Compare to 4 component model in Python
  - Compare to results of SCK CEN through-diffusion

From: On Multi-Component Gas Migration in Single-Phase Systems

Calculated and measured results for the through-diffusion experiment

- **THEBES**
  - two inert and non-condensable gas mixture formulation for isothermal, no water flow and constant volume soil in the framework
  - Reproduction of SCK CEN through-diffusion

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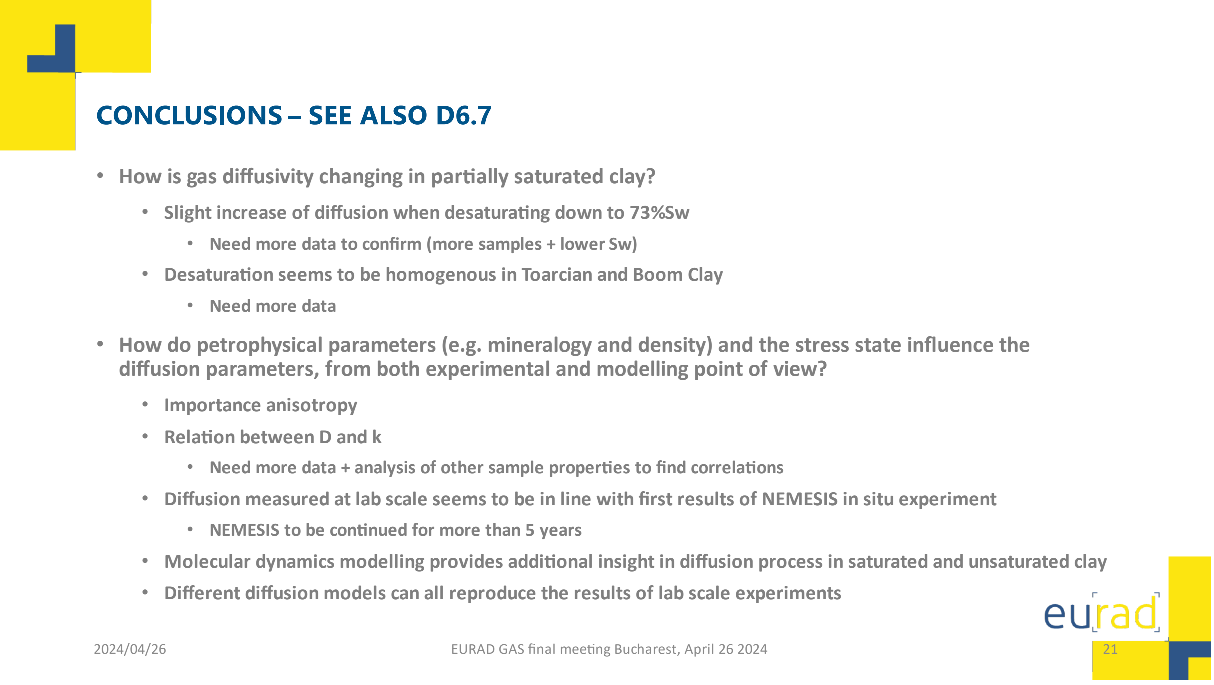
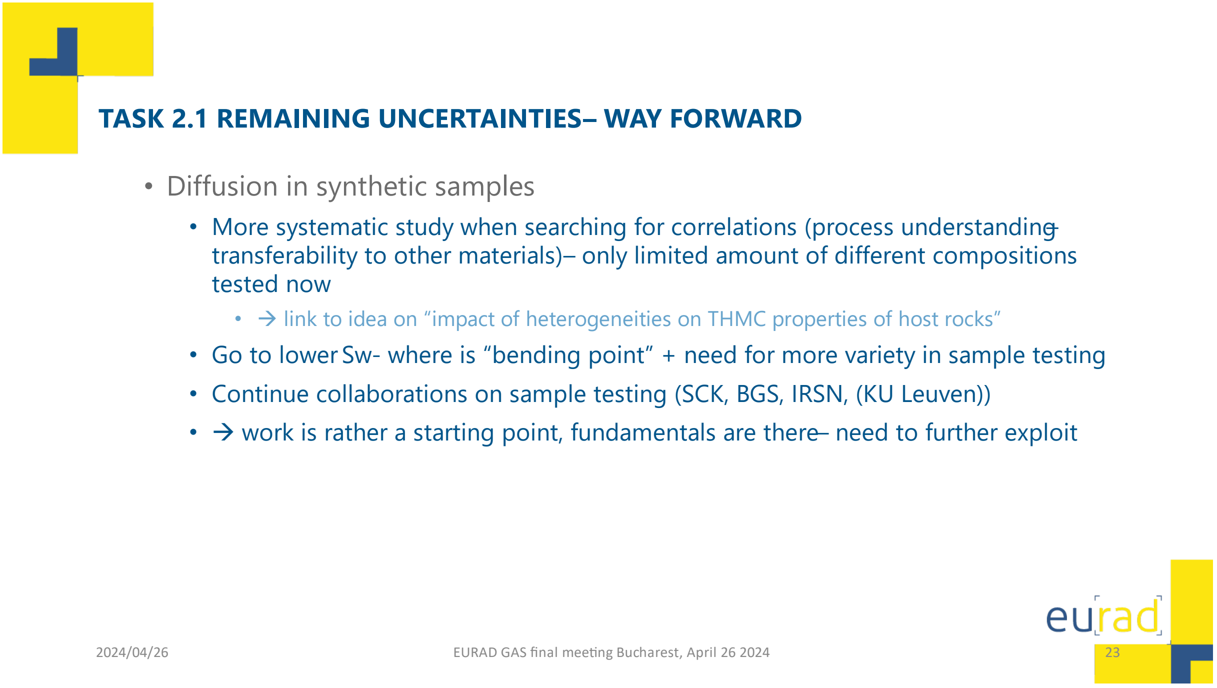


CONCLUSIONS – SEE ALSO D6.7

- How is gas diffusivity changing in partially saturated clay?
  - Slight increase of diffusion when desaturating down to 73%Sw
    - Need more data to confirm (more samples + lower Sw)
  - Desaturation seems to be homogenous in Toarcian and Boom Clay
    - Need more data
- How do petrophysical parameters (e.g. mineralogy and density) and the stress state influence the diffusion parameters, from both experimental and modelling point of view?
  - Importance anisotropy
  - Relation between D and k
    - Need more data + analysis of other sample properties to find correlations
  - Diffusion measured at lab scale seems to be in line with first results of NEMESIS in situ experiment
    - NEMESIS to be continued for more than 5 years
  - Molecular dynamics modelling provides additional insight in diffusion process in saturated and unsaturated clay
  - Different diffusion models can all reproduce the results of lab scale experiments

SOME HIGHLIGHTS AND WAY FORWARD

- **Highlights**
  - Important progress made, certain consistency in data (different set-ups, different materials, repeats, …)
  - Excellent collaborations: mobilities, sample exchange, working groups like BC cluster and diffusion cluster, joint papers & presentations, …
- **Way forward**
  - The work is not yet done …
    - Need more data in systematic study when searching for correlations (process understanding– transferability to other materials)
    - Confirm impact of desaturation + improve system understanding
    - Collect more data on sample desaturation process
    - Continue collaborations on sample testing (SCK, BGS, IRSN, (KU Leuven))
  - Work is rather a starting point, fundamentals are there – need to further exploit – “harvest the fruits”



TASK 2.1 REMAINING UNCERTAINTIES– WAY FORWARD

- Diffusion in synthetic samples
  - More systematic study when searching for correlations (process understanding + transferability to other materials)– only limited amount of different compositions tested now
    - → link to idea on "impact of heterogeneities on THMC properties of host rocks"
  - Go to lower Sw- where is "bending point" + need for more variety in sample testing
  - Continue collaborations on sample testing (SCK, BGS, IRSN, (KU Leuven))
  - → work is rather a starting point, fundamentals are there– need to further exploit

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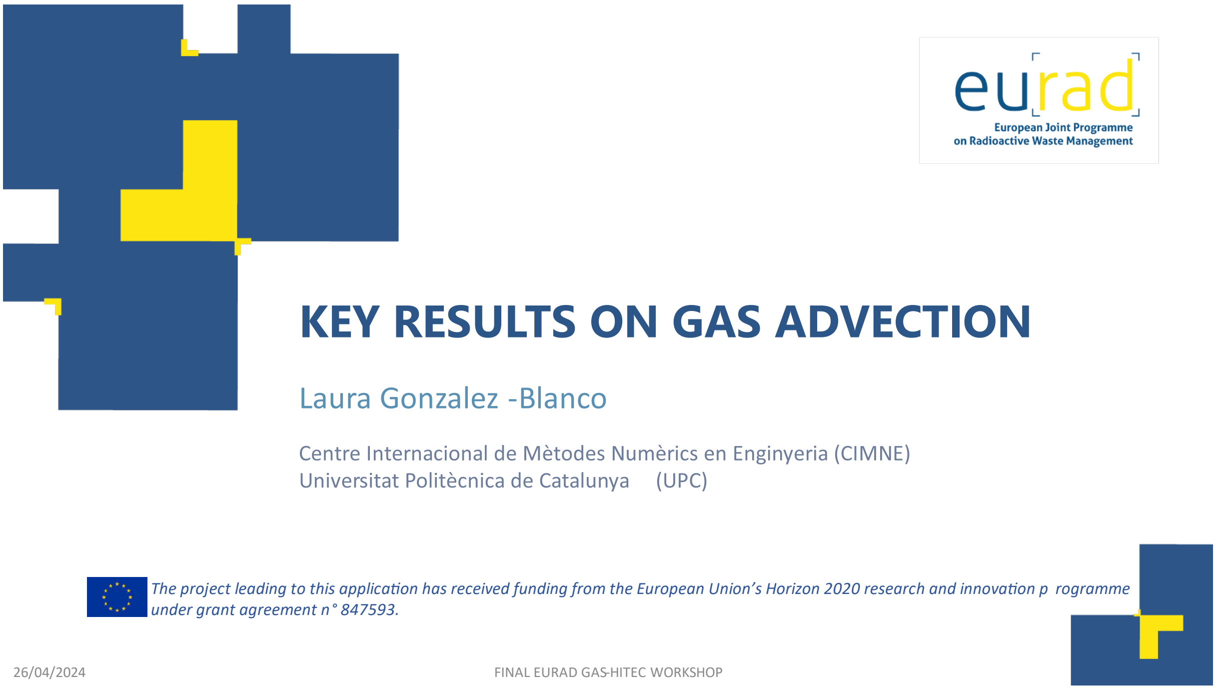
2.3 Key results on gas advection



KEY RESULTS ON GAS ADVECTION

Laura Gonzalez -Blanco

Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE)
Universitat Politècnica de Catalunya (UPC)

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n° 847593.

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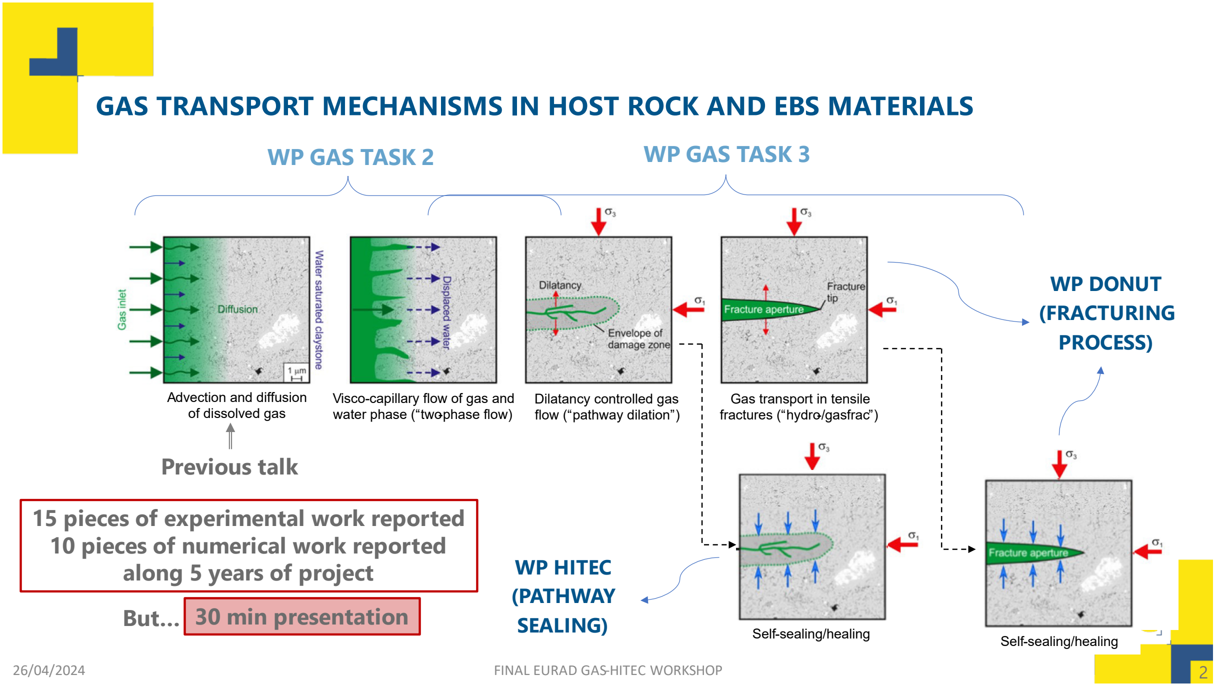

GAS TRANSPORT MECHANISMS IN HOST ROCK AND EBS MATERIALS

Advection and diffusion of dissolved gas

Visco-capillary flow of gas and water phase ("twophase flow)

Dilatancy controlled gas flow ("pathway dilation")

Gas transport in tensile fractures ("hydro/gasfrac")

Self-sealing/healing

Self-sealing/healing

15 pieces of experimental work reported
10 pieces of numerical work reported
along 5 years of project

But… 30 min presentation

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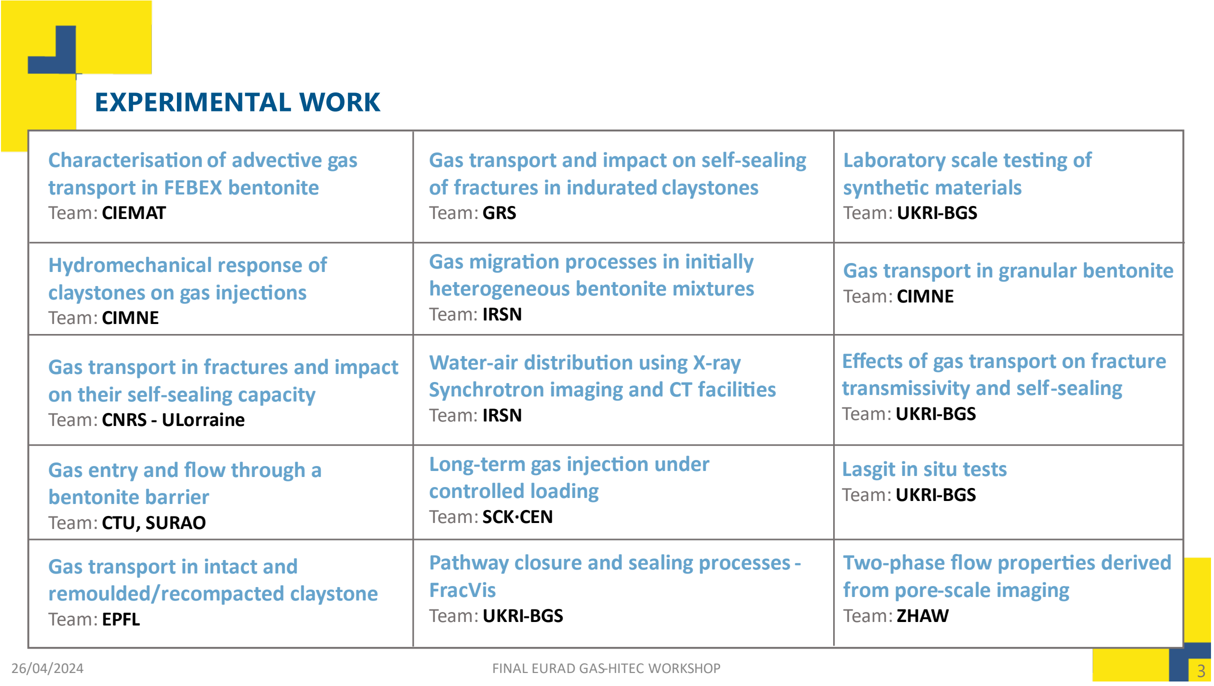

EXPERIMENTAL WORK

Characterisation of advective gas transport in FEBEX bentonite Team: **CIEMAT**	Gas transport and impact on self-sealing of fractures in indurated claystones Team: **GRS**	Laboratory scale testing of synthetic materials Team: **UKRI-BGS**
Hydromechanical response of claystones on gas injections Team: **CIMNE**	Gas migration processes in initially heterogeneous bentonite mixtures Team: **IRSN**	Gas transport in granular bentonite Team: **CIMNE**
Gas transport in fractures and impact on their self-sealing capacity Team: **CNRS - ULorraine**	Water-air distribution using X-ray Synchrotron imaging and CT facilities Team: **IRSN**	Effects of gas transport on fracture transmissivity and self-sealing Team: **UKRI-BGS**
Gas entry and flow through a bentonite barrier Team: **CTU, SURAO**	Long-term gas injection under controlled loading Team: **SCK·CEN**	Lasgit in situ tests Team: **UKRI-BGS**
Gas transport in intact and remoulded/recompacted claystone Team: **EPFL**	Pathway closure and sealing processes - FracVis Team: **UKRI-BGS**	Two-phase flow properties derived from pore-scale imaging Team: **ZHAW**

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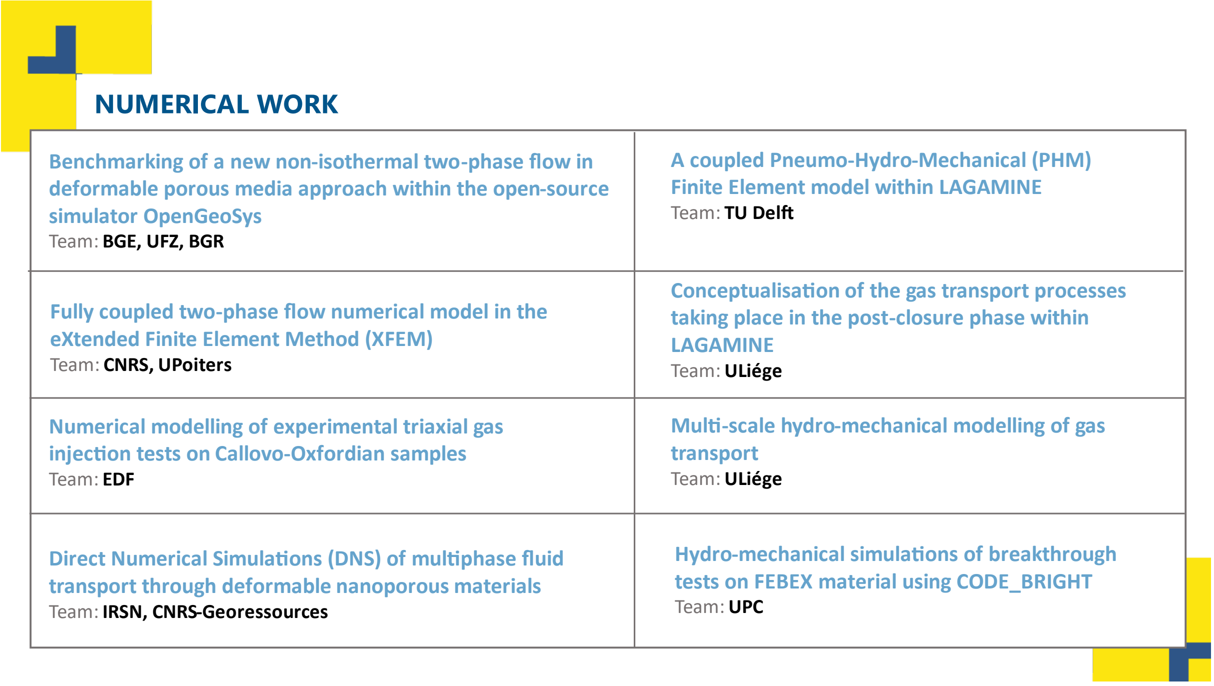
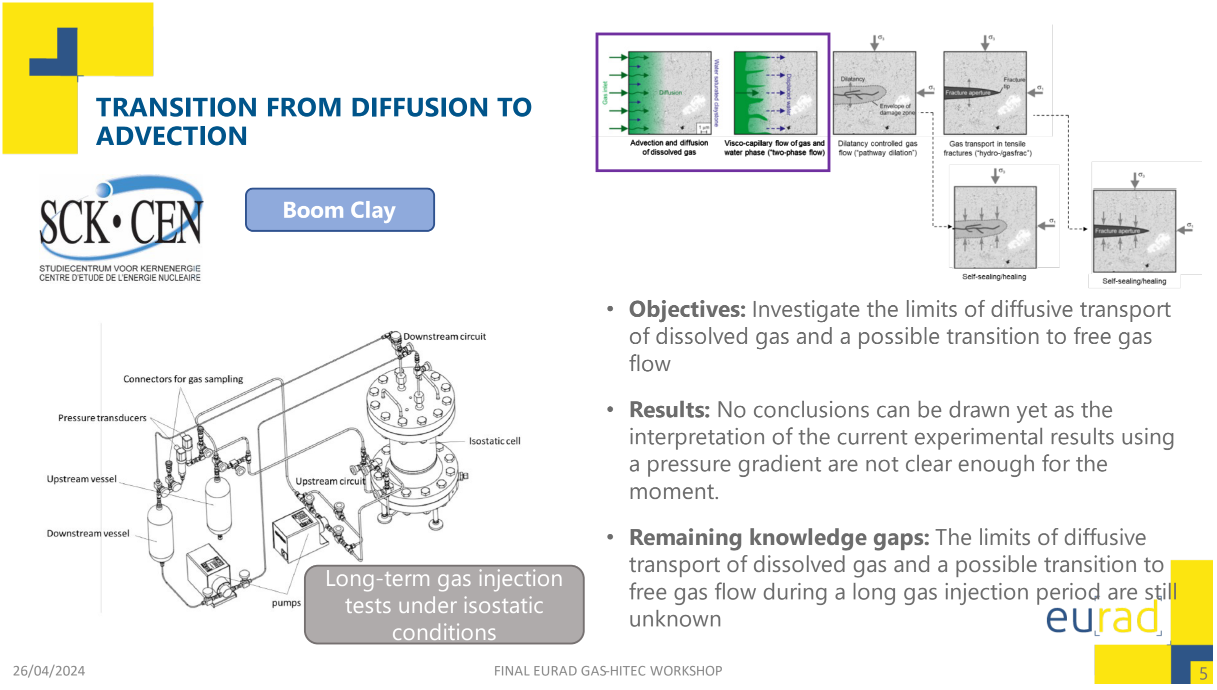


NUMERICAL WORK

Benchmarking of a new non-isothermal two-phase flow in deformable porous media approach within the open-source simulator OpenGeoSys Team: **BGE, UFZ, BGR**	A coupled Pneumo-Hydro-Mechanical (PHM) Finite Element model within LAGAMINE Team: **TU Delft**
Fully coupled two-phase flow numerical model in the eXtended Finite Element Method (XFEM) Team: **CNRS, UPoiters**	Conceptualisation of the gas transport processes taking place in the post-closure phase within LAGAMINE Team: **ULiége**
Numerical modelling of experimental triaxial gas injection tests on Callovo-Oxfordian samples Team: **EDF**	Multi-scale hydro-mechanical modelling of gas transport Team: **ULiége**
Direct Numerical Simulations (DNS) of multiphase fluid transport through deformable nanoporous materials Team: **IRSN, CNRS-Georessources**	Hydro-mechanical simulations of breakthrough tests on FEBEX material using CODE_BRIGHT Team: **UPC**



TRANSITION FROM DIFFUSION TO ADVECTION

STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

Boom Clay

Long-term gas injection tests under isostatic conditions

- **Objectives:** Investigate the limits of diffusive transport of dissolved gas and a possible transition to free gas flow
- **Results:** No conclusions can be drawn yet as the interpretation of the current experimental results using a pressure gradient are not clear enough for the moment.
- **Remaining knowledge gaps:** The limits of diffusive transport of dissolved gas and a possible transition to free gas flow during a long gas injection period are still unknown

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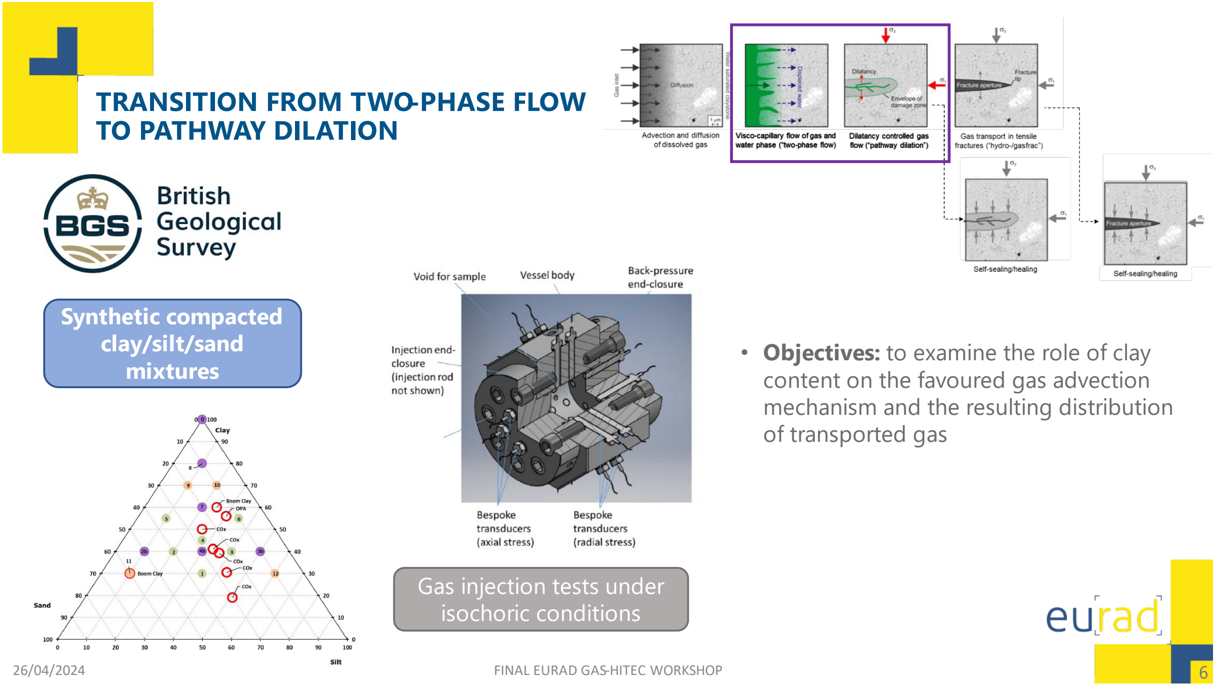

TRANSITION FROM TWO-PHASE FLOW TO PATHWAY DILATION

British Geological Survey

Synthetic compacted clay/silt/sand mixtures

Gas injection tests under isochoric conditions

- **Objectives:** to examine the role of clay content on the favoured gas advection mechanism and the resulting distribution of transported gas

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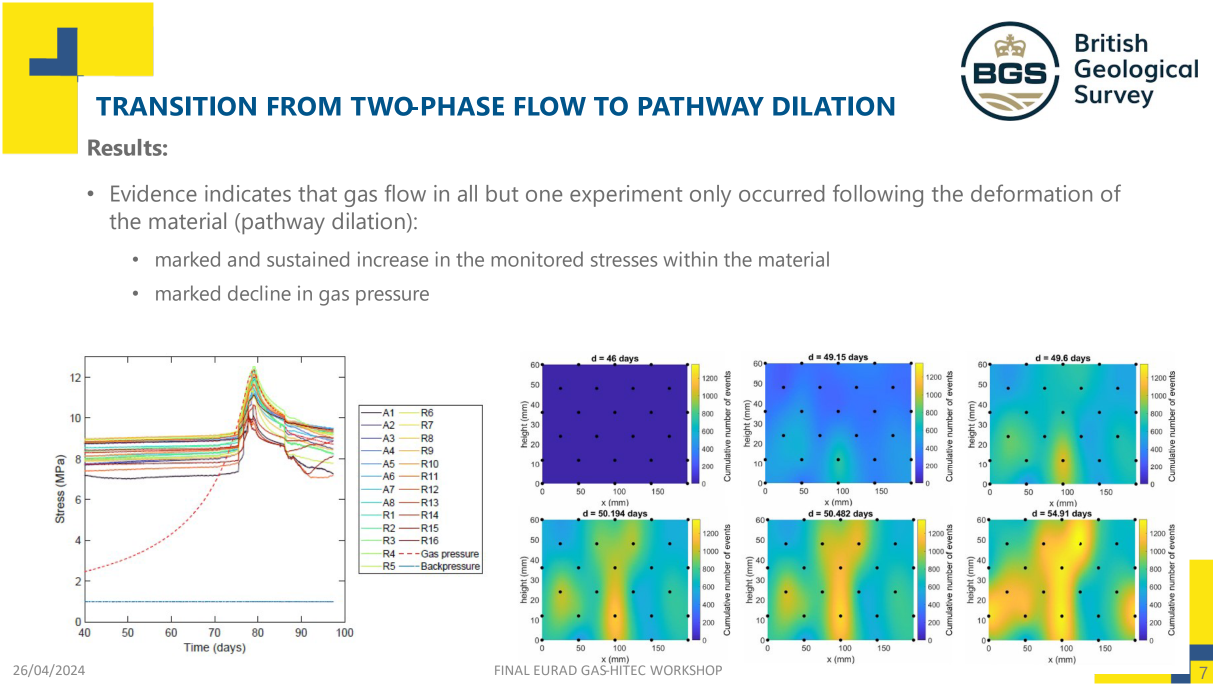

TRANSITION FROM TWO-PHASE FLOW TO PATHWAY DILATION

Results:

- Evidence indicates that gas flow in all but one experiment only occurred following the deformation of the material (pathway dilation):
    - marked and sustained increase in the monitored stresses within the material
    - marked decline in gas pressure

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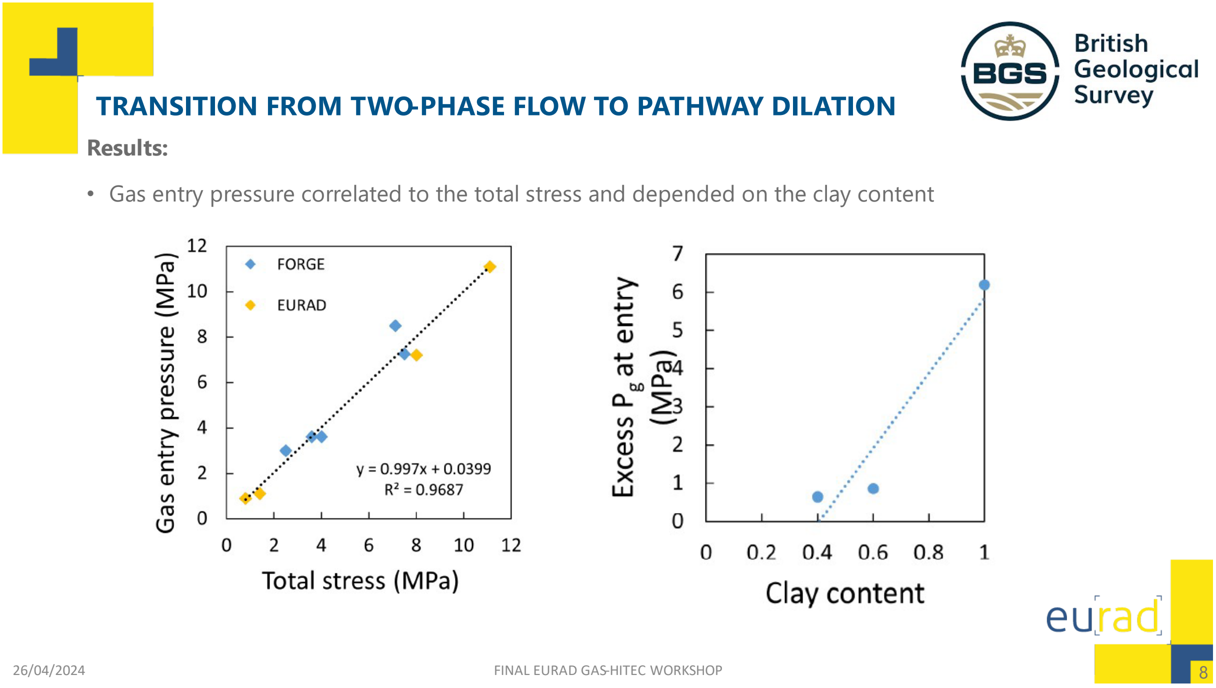

TRANSITION FROM TWO-PHASE FLOW TO PATHWAY DILATION

Results:

- Gas entry pressure correlated to the total stress and depended on the clay content

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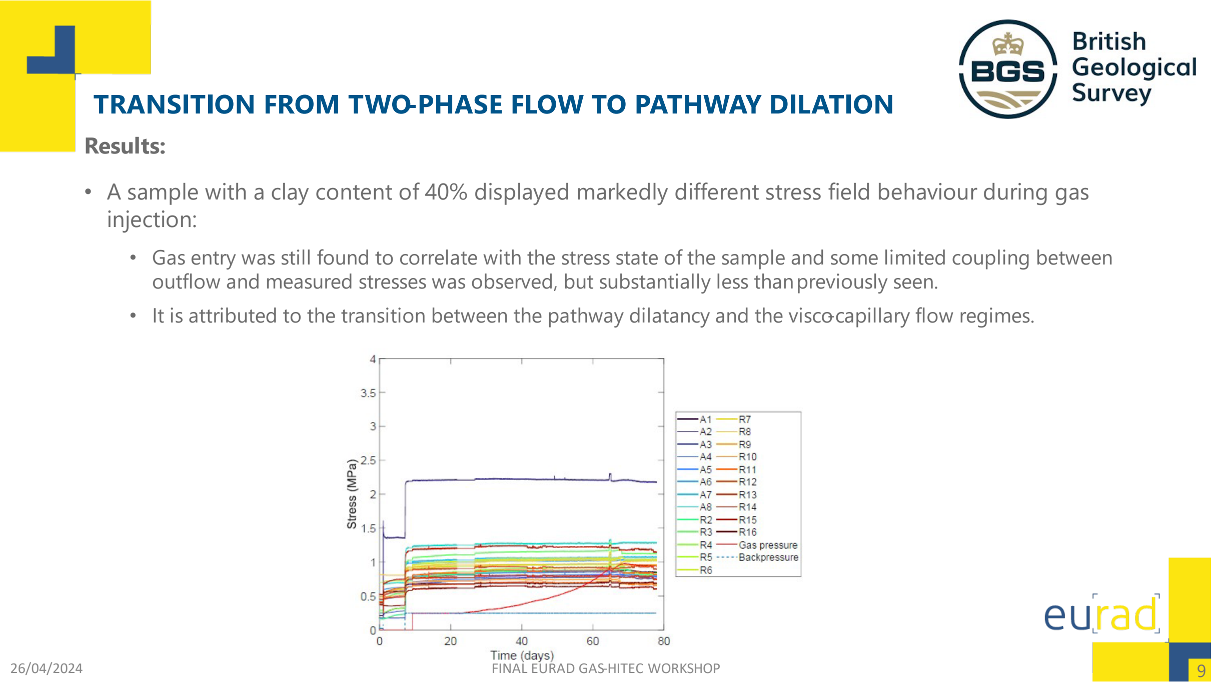

British Geological Survey

TRANSITION FROM TWO-PHASE FLOW TO PATHWAY DILATION

Results:

- A sample with a clay content of 40% displayed markedly different stress field behaviour during gas injection:
  - Gas entry was still found to correlate with the stress state of the sample and some limited coupling between outflow and measured stresses was observed, but substantially less than previously seen.
  - It is attributed to the transition between the pathway dilatancy and the visco-capillary flow regimes.

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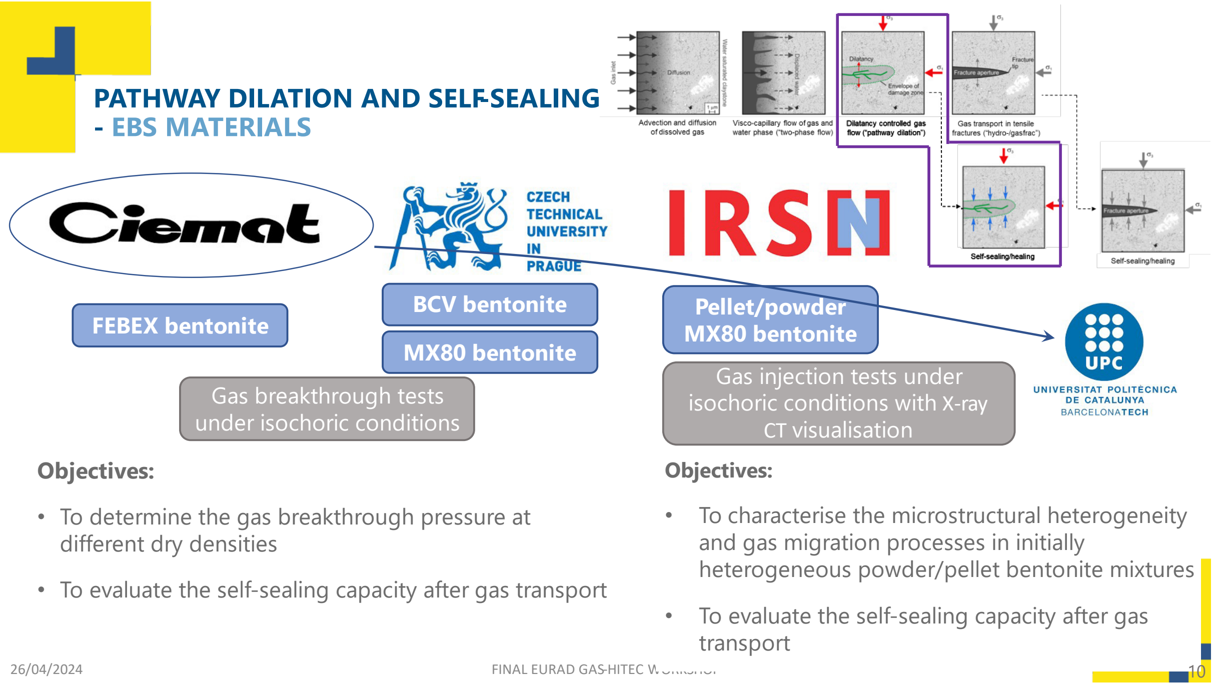

PATHWAY DILATION AND SELF-SEALING - EBS MATERIALS

FEBEX bentonite

BCV bentonite

MX80 bentonite

Gas breakthrough tests under isochoric conditions

Pellet/powder MX80 bentonite

Gas injection tests under isochoric conditions with X-ray CT visualisation

Objectives:

- To determine the gas breakthrough pressure at different dry densities
- To evaluate the self-sealing capacity after gas transport

Objectives:

- To characterise the microstructural heterogeneity and gas migration processes in initially heterogeneous powder/pellet bentonite mixtures
- To evaluate the self-sealing capacity after gas transport

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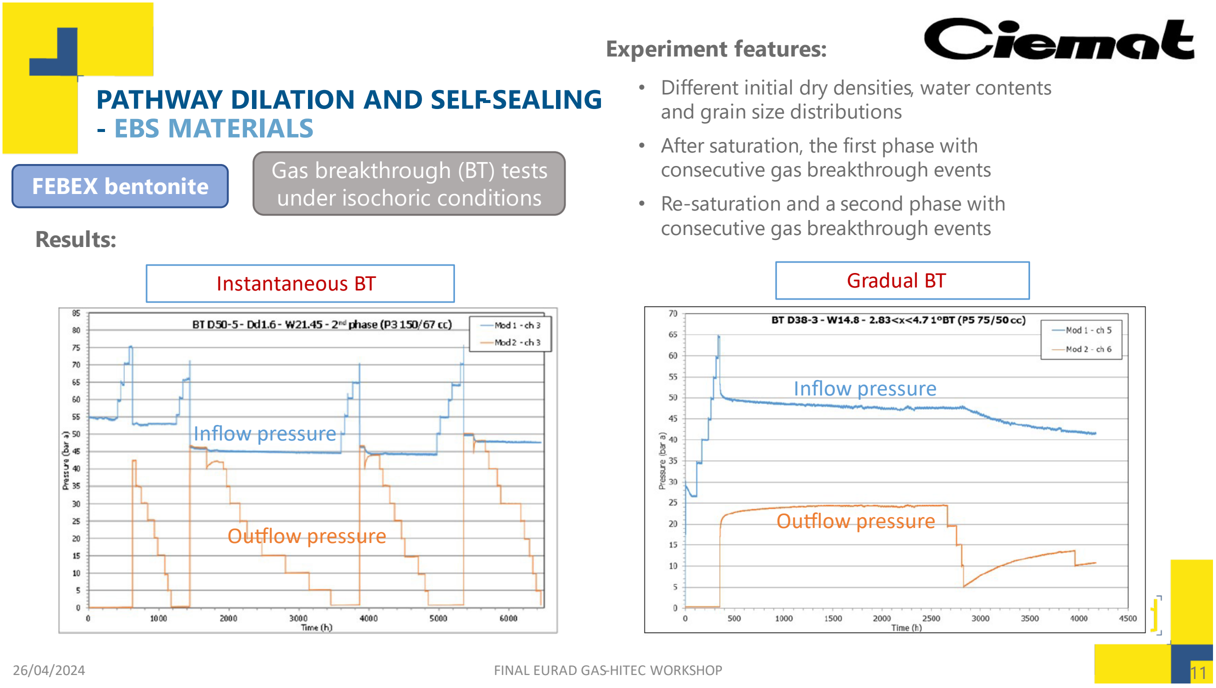

PATHWAY DILATION AND SELF-SEALING - EBS MATERIALS

FEBEX bentonite

Gas breakthrough (BT) tests under isochoric conditions

Experiment features:

- Different initial dry densities, water contents and grain size distributions
- After saturation, the first phase with consecutive gas breakthrough events
- Re-saturation and a second phase with consecutive gas breakthrough events

Results:

Instantaneous BT

Gradual BT

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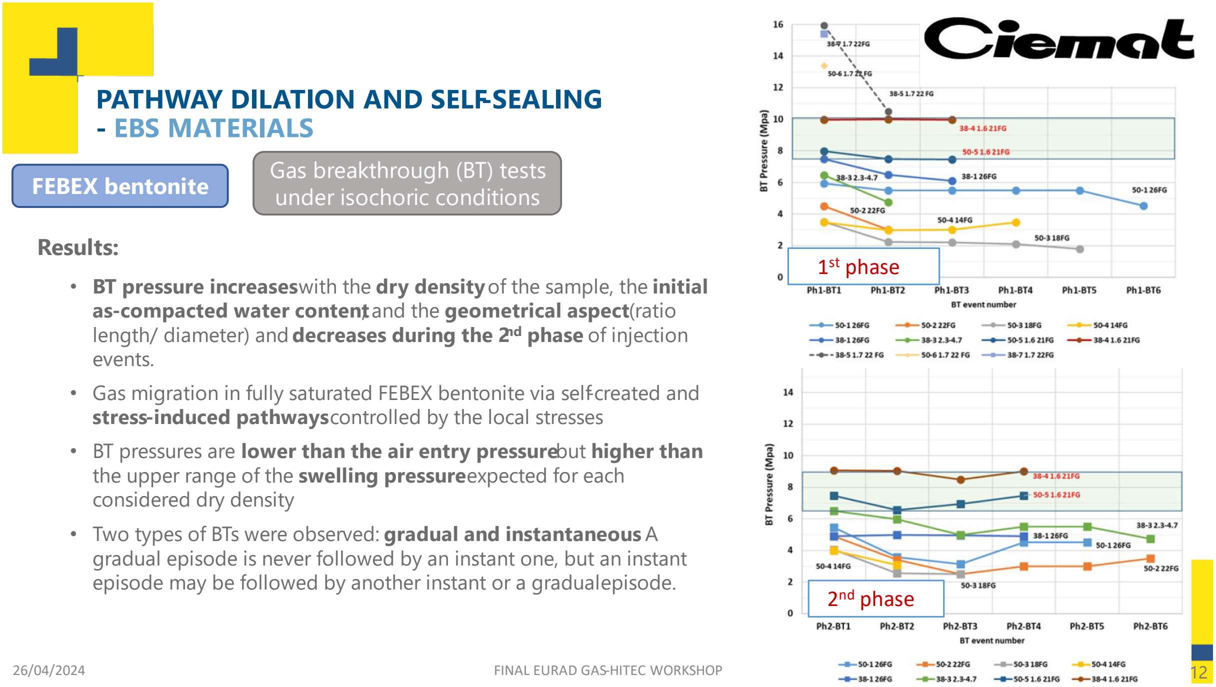

PATHWAY DILATION AND SELF-SEALING - EBS MATERIALS

FEBEX bentonite

Gas breakthrough (BT) tests under isochoric conditions

Results:

- **BT pressure increases** with the **dry density** of the sample, the **initial as-compacted water content**, and the **geometrical aspect** (ratio length/ diameter) and **decreases during the 2nd phase** of injection events.
- Gas migration in fully saturated FEBEX bentonite via self-created and **stress-induced pathways** controlled by the local stresses
- BT pressures are **lower than the air entry pressure** but **higher than** the upper range of the **swelling pressure** expected for each considered dry density
- Two types of BTs were observed: **gradual and instantaneous**. A gradual episode is never followed by an instant one, but an instant episode may be followed by another instant or a gradual episode.

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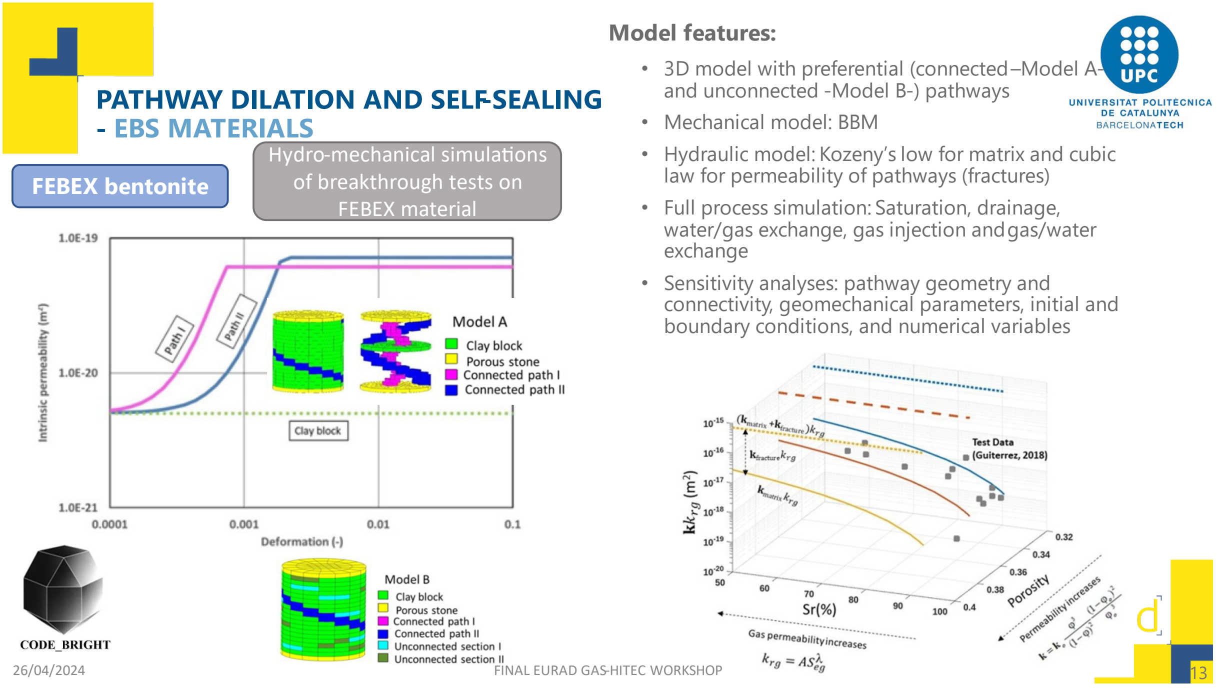

PATHWAY DILATION AND SELF-SEALING - EBS MATERIALS

FEBEX bentonite

Hydro-mechanical simulations of breakthrough tests on FEBEX material

Model features:

- 3D model with preferential (connected –Model A- and unconnected -Model B-) pathways
- Mechanical model: BBM
- Hydraulic model: Kozeny's low for matrix and cubic law for permeability of pathways (fractures)
- Full process simulation: Saturation, drainage, water/gas exchange, gas injection and gas/water exchange
- Sensitivity analyses: pathway geometry and connectivity, geomechanical parameters, initial and boundary conditions, and numerical variables

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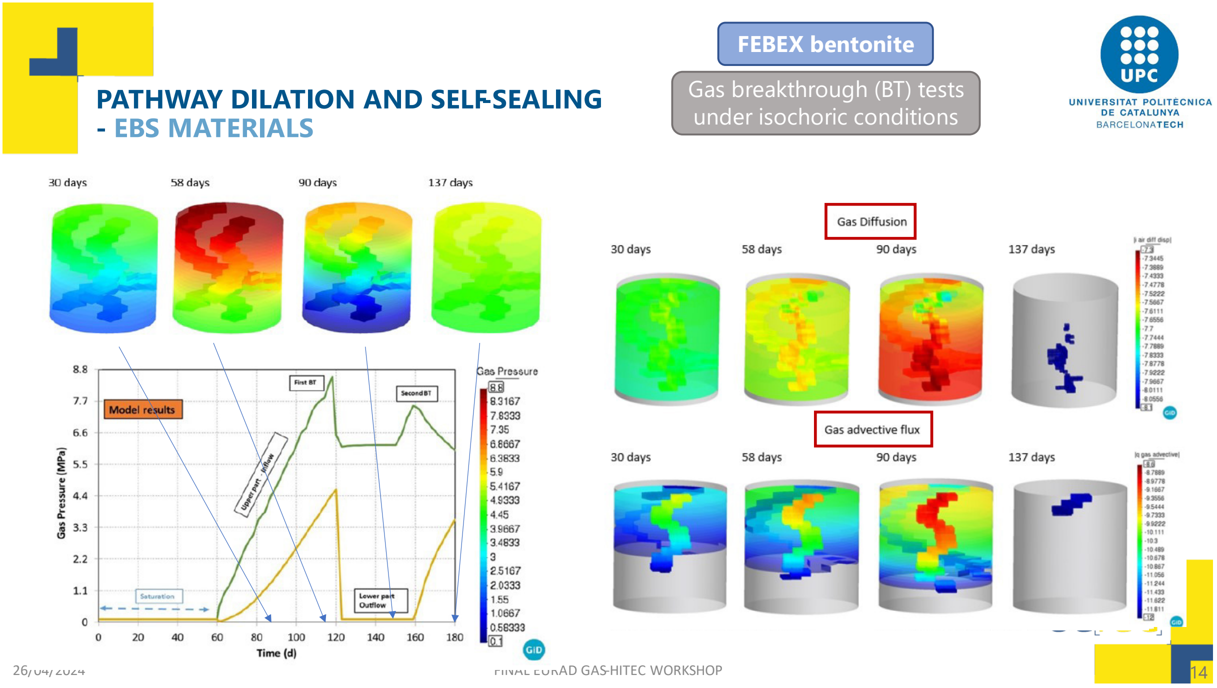

PATHWAY DILATION AND SELF-SEALING - EBS MATERIALS

FEBEX bentonite

Gas breakthrough (BT) tests under isochoric conditions

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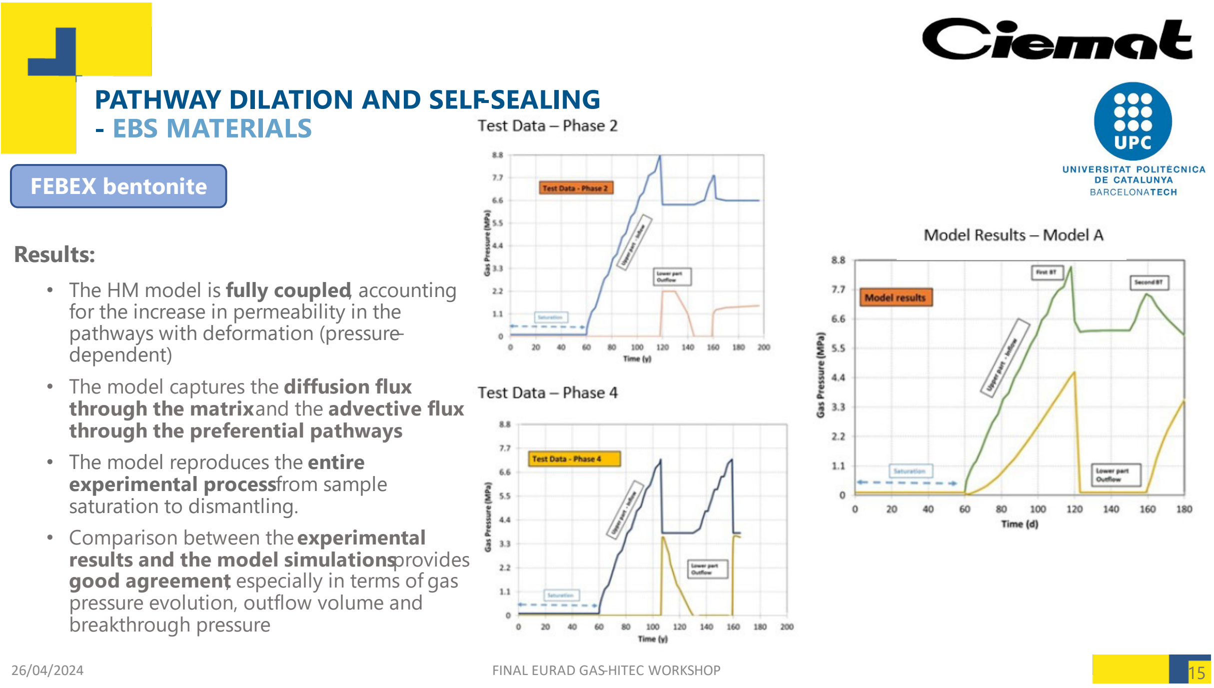

PATHWAY DILATION AND SELF-SEALING - EBS MATERIALS

FEBEX bentonite

Results:

- The HM model is **fully coupled**, accounting for the increase in permeability in the pathways with deformation (pressure-dependent)
- The model captures the **diffusion flux through the matrix** and the **advective flux through the preferential pathways**
- The model reproduces the **entire experimental process** from sample saturation to dismantling.
- Comparison between the **experimental results and the model simulations** provides **good agreement**, especially in terms of gas pressure evolution, outflow volume and breakthrough pressure

Test Data – Phase 2

Test Data – Phase 4

Model Results – Model A

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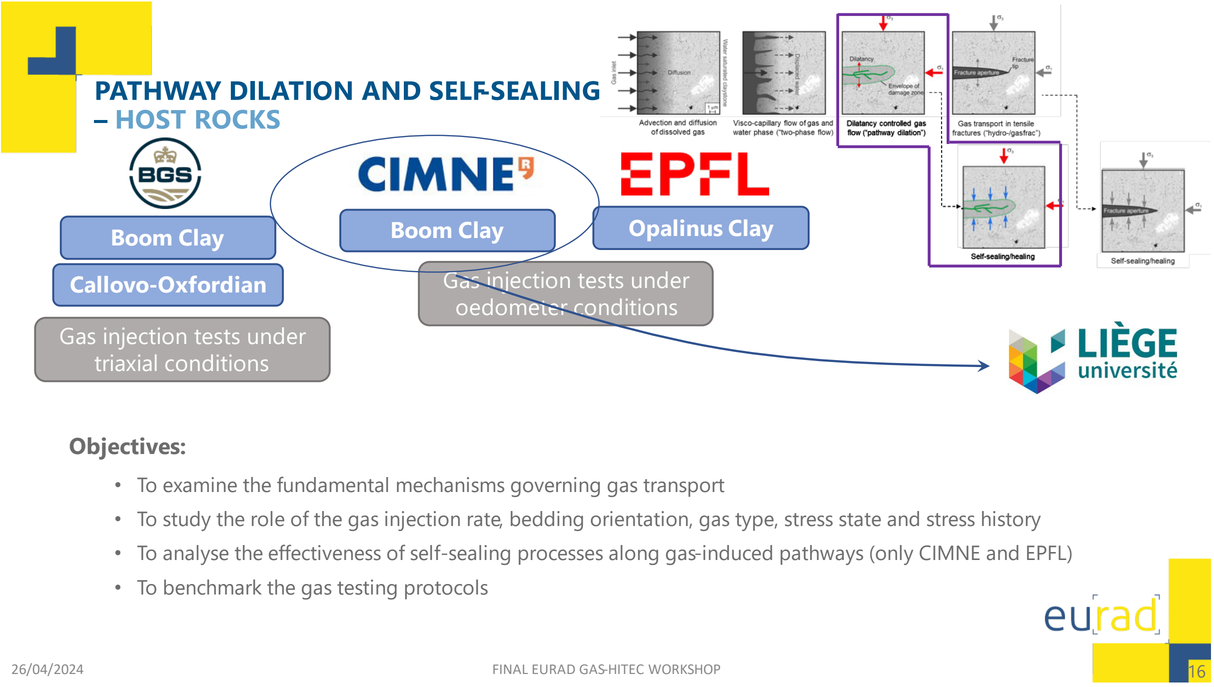

PATHWAY DILATION AND SELF-SEALING – HOST ROCKS

Boom Clay

Callovo-Oxfordian

Gas injection tests under triaxial conditions

Boom Clay

Opalinus Clay

Gas injection tests under oedometer conditions

Objectives:

- To examine the fundamental mechanisms governing gas transport
- To study the role of the gas injection rate, bedding orientation, gas type, stress state and stress history
- To analyse the effectiveness of self-sealing processes along gas-induced pathways (only CIMNE and EPFL)
- To benchmark the gas testing protocols

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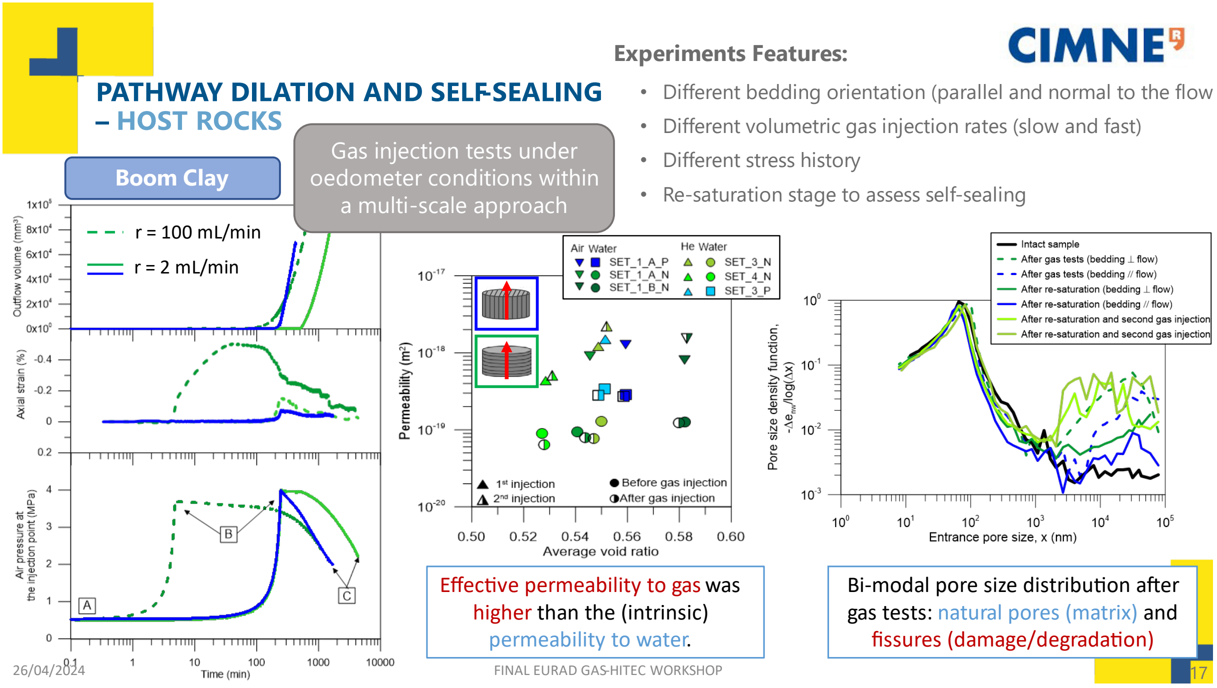

PATHWAY DILATION AND SELF-SEALING – HOST ROCKS

Boom Clay

Gas injection tests under oedometer conditions within a multi-scale approach

Experiments Features:

- Different bedding orientation (parallel and normal to the flow
- Different volumetric gas injection rates (slow and fast)
- Different stress history
- Re-saturation stage to assess self-sealing

Effective permeability to gas was higher than the (intrinsic) permeability to water.

Bi-modal pore size distribution after gas tests: natural pores (matrix) and fissures (damage/degradation)

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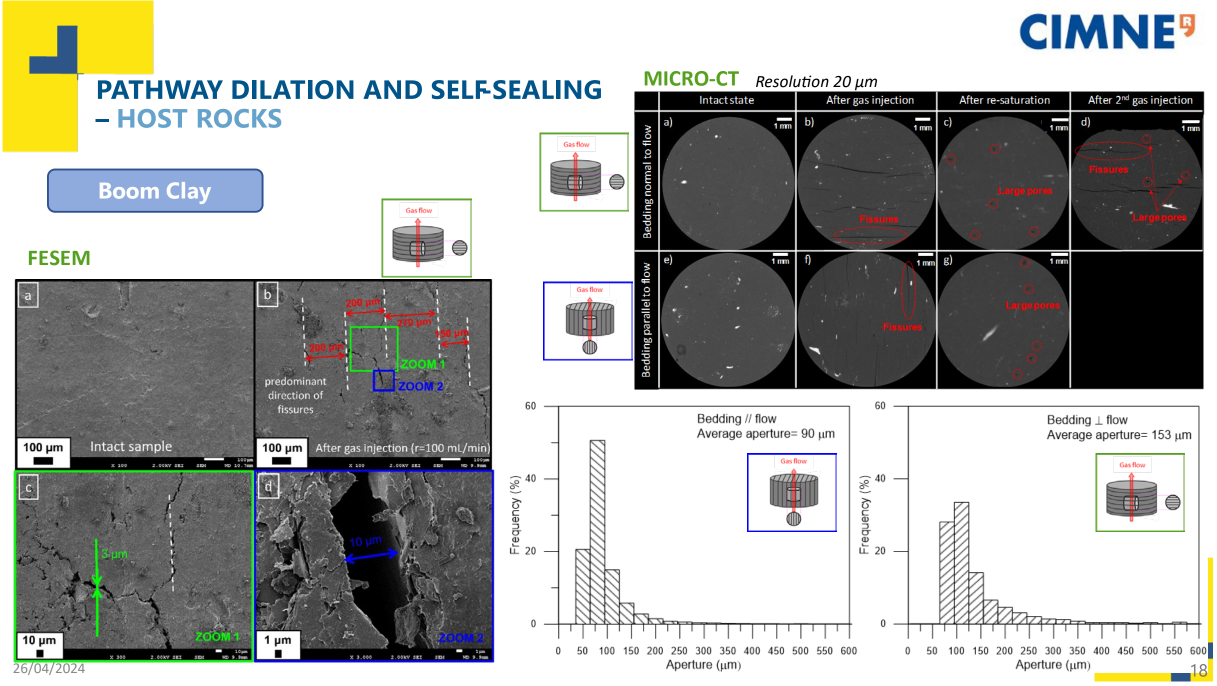

PATHWAY DILATION AND SELF-SEALING – HOST ROCKS

Boom Clay

FESEM

MICRO-CT *Resolution 20 μm*

Bedding // flow
Average aperture= 90 μm

Bedding ⊥ flow
Average aperture= 153 μm

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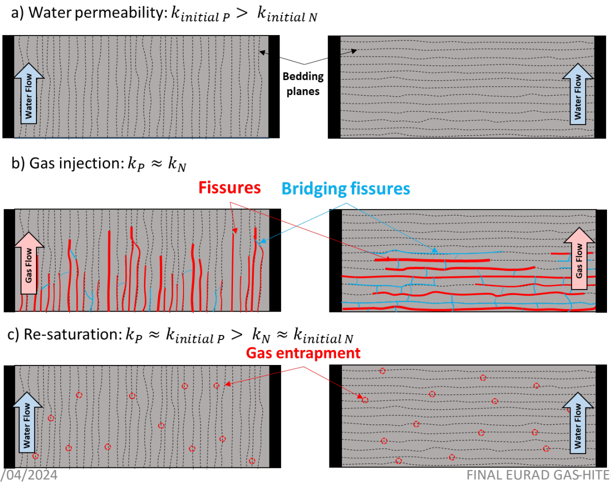
PATHWAY DILATION AND SELF-SEALING – HOST ROCKS

Conceptualization:



Results:

- Intrinsic water permeability presented anisotropy
- Gas flowed at pressures lower than the minimum principal stress
- During gas injection small deformations were recorded in both orientations and are larger for higher injection rates
- Effective gas permeability was higher than water permeability and without anisotropic features
- Gas mainly flowed through dilatant preferential pathways (fissures), confirmed by microstructural tests
- After re-saturation, initial values of water permeability were restored (effective self-sealing) despite the detection of some pores due to gas entrapment

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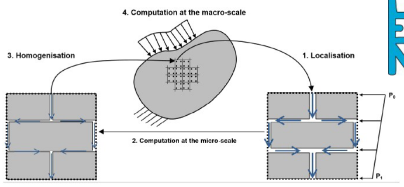
PATHWAY DILATION AND SELF-SEALING – HOST ROCKS

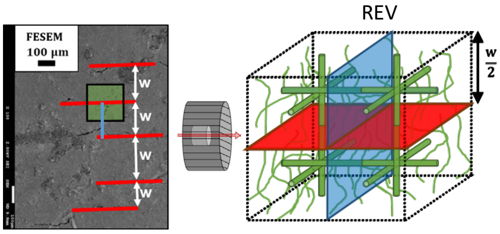
Multi-scale hydro-mechanical modelling of gas transport

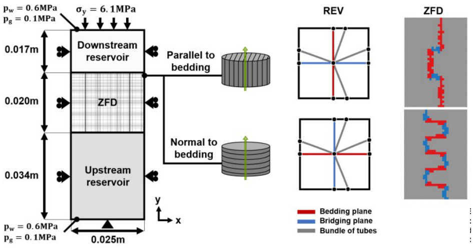


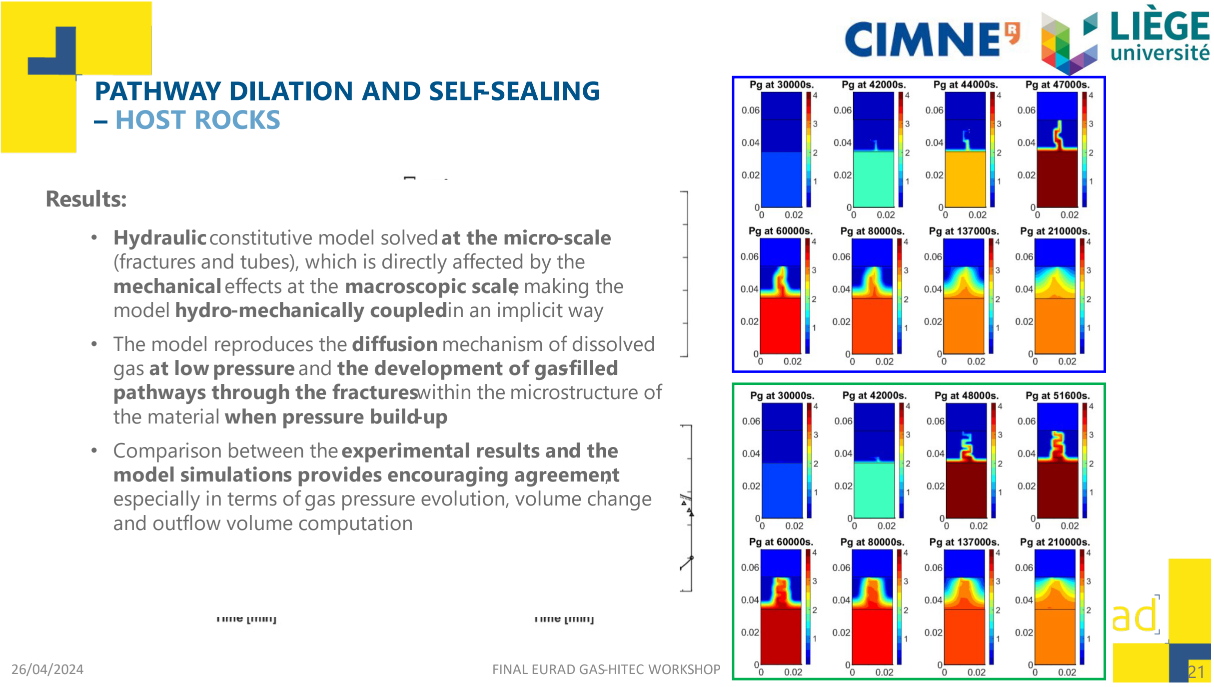
Model features:

- Constitutive model at the micro-scale (REV) integrated into a multi-scale scheme using homogenisation and localisation techniques for the transitions to the macro-scale.
- Advection-diffusion model for multiphase flow along fractures and tubes embedded in a REV
- HM coupling: dependency of the permeability on the fracture and tube apertures (flow channel model), which are stress-dependent.

- ▶ **1 fracture = bedding plane + a network of connected porosity**
- ▶ **The pore network is substituted with an assembly of tubes**
- ▶ **1 thinner fracture = bridging plane**







PATHWAY DILATION AND SELF-SEALING – HOST ROCKS

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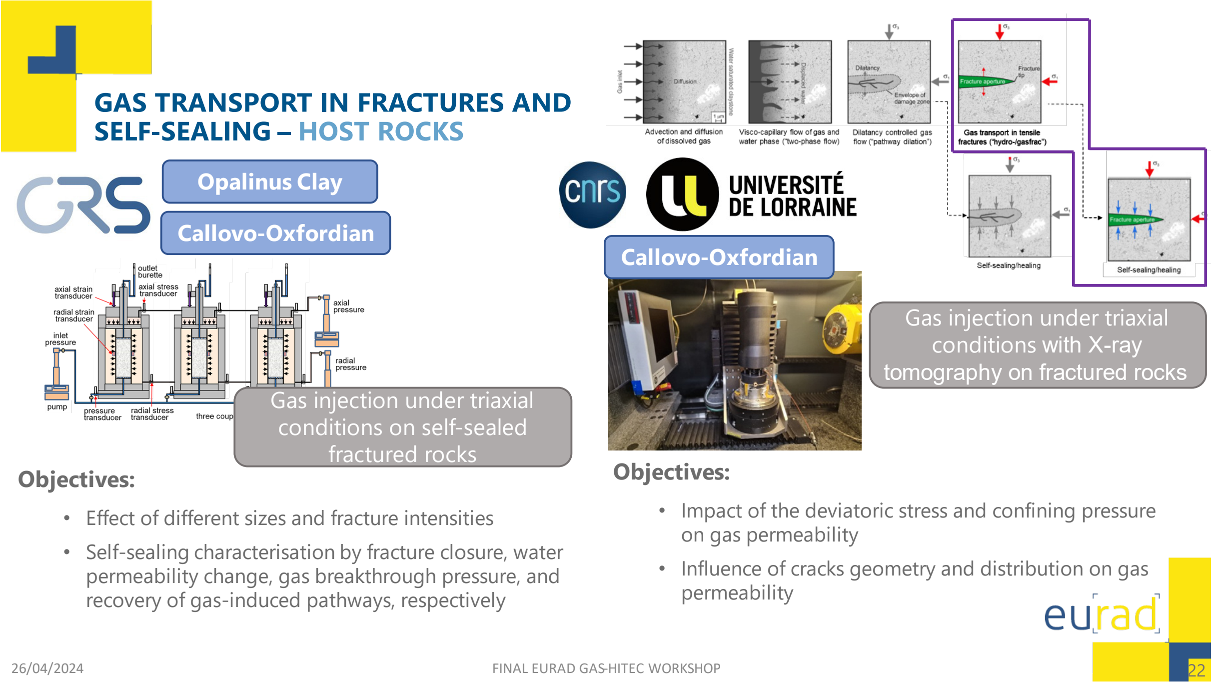
Results:

- **Hydraulic** constitutive model solved **at the micro-scale** (fractures and tubes), which is directly affected by the **mechanical** effects at the **macroscopic scale**, making the model **hydro-mechanically coupled** in an implicit way
- The model reproduces the **diffusion** mechanism of dissolved gas **at low pressure** and **the development of gas-filled pathways through the fractures** within the microstructure of the material **when pressure build-up**
- Comparison between the **experimental results and the model simulations provides encouraging agreement** especially in terms of gas pressure evolution, volume change and outflow volume computation



GAS TRANSPORT IN FRACTURES AND SELF-SEALING – HOST ROCKS

GRS

Opalinus Clay

Callovo-Oxfordian

Gas injection under triaxial conditions on self-sealed fractured rocks

Objectives:

- Effect of different sizes and fracture intensities
- Self-sealing characterisation by fracture closure, water permeability change, gas breakthrough pressure, and recovery of gas-induced pathways, respectively

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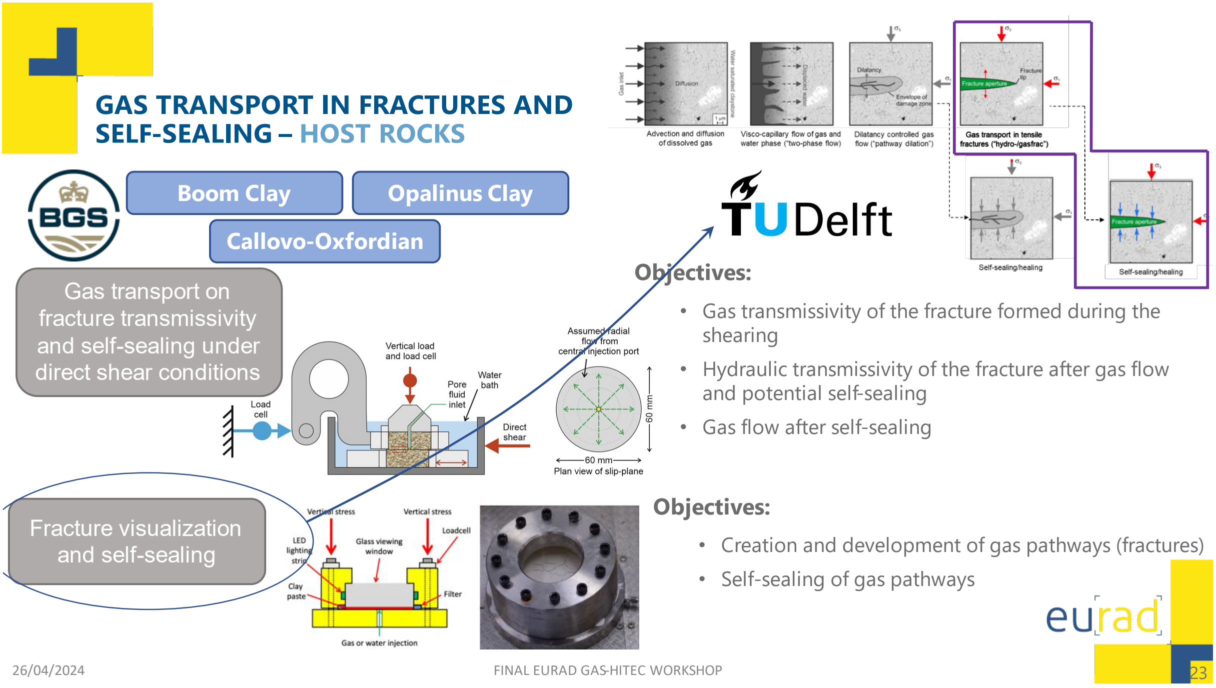
Callovo-Oxfordian

Gas injection under triaxial conditions with X-ray tomography on fractured rocks

Objectives:

- Impact of the deviatoric stress and confining pressure on gas permeability
- Influence of cracks geometry and distribution on gas permeability



GAS TRANSPORT IN FRACTURES AND SELF-SEALING – HOST ROCKS

Boom Clay

Opalinus Clay

Callovo-Oxfordian

Gas transport on fracture transmissivity and self-sealing under direct shear conditions

Objectives:

- Gas transmissivity of the fracture formed during the shearing
- Hydraulic transmissivity of the fracture after gas flow and potential self-sealing
- Gas flow after self-sealing

Fracture visualization and self-sealing

Objectives:

- Creation and development of gas pathways (fractures)
- Self-sealing of gas pathways

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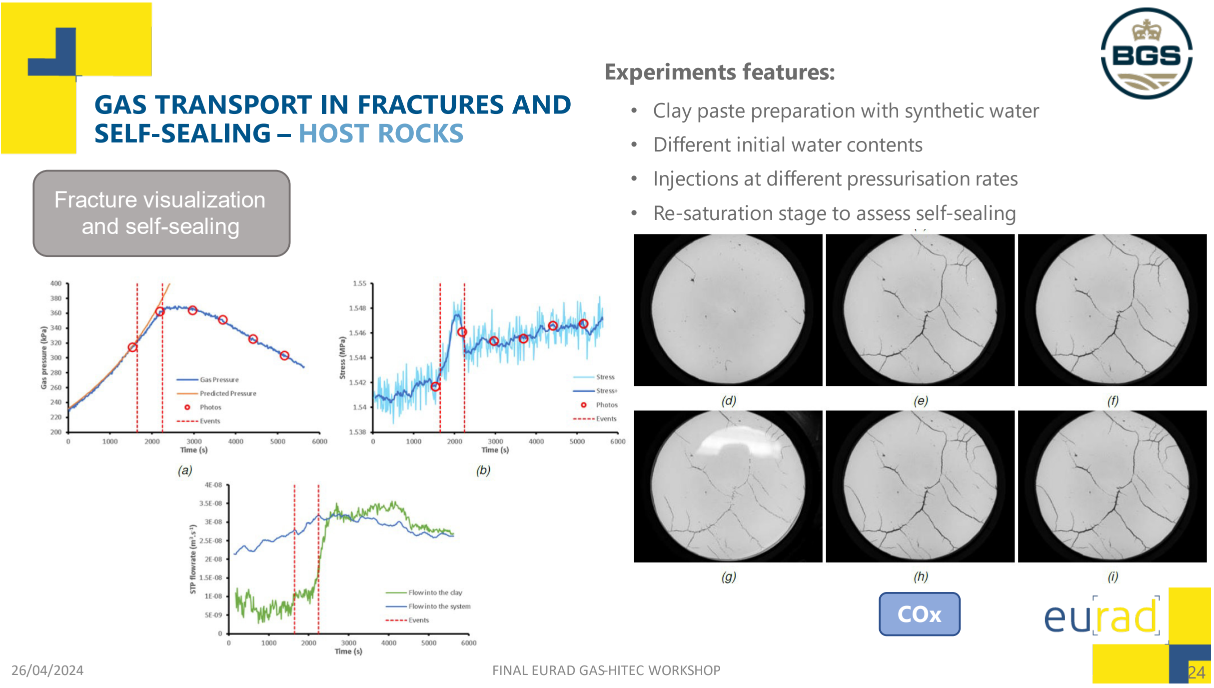

GAS TRANSPORT IN FRACTURES AND SELF-SEALING – HOST ROCKS

Fracture visualization and self-sealing

Experiments features:

- Clay paste preparation with synthetic water
- Different initial water contents
- Injections at different pressurisation rates
- Re-saturation stage to assess self-sealing

COx

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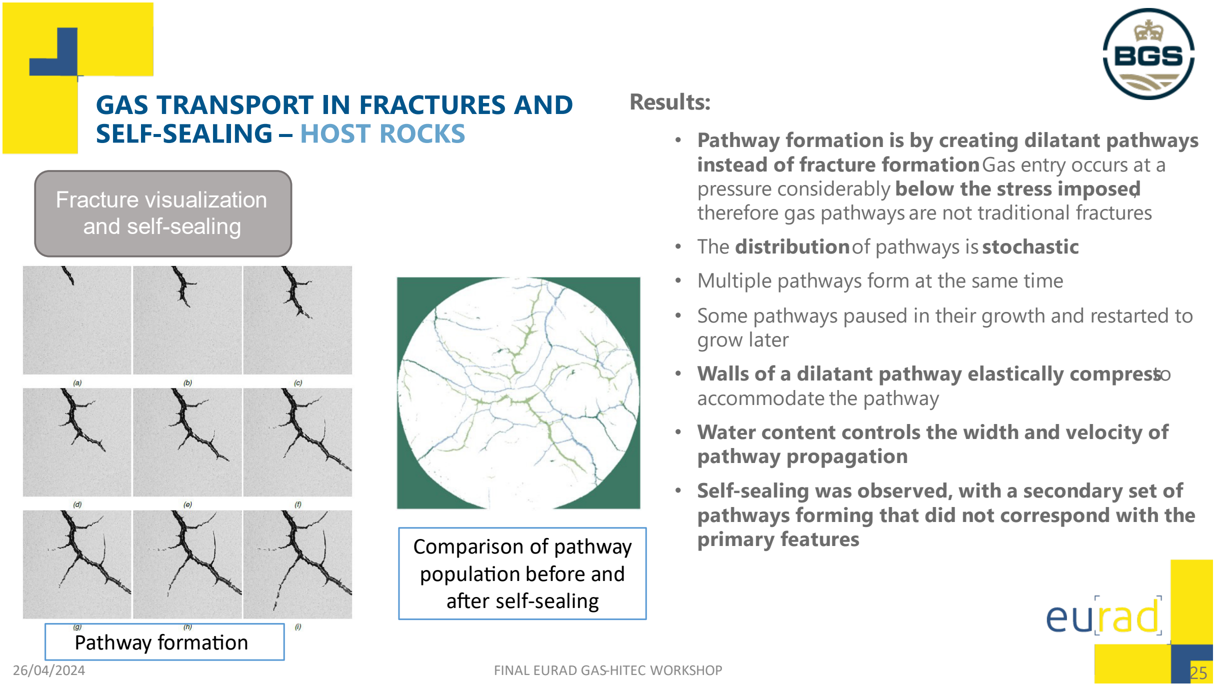

GAS TRANSPORT IN FRACTURES AND SELF-SEALING – HOST ROCKS

Fracture visualization and self-sealing

Pathway formation

Comparison of pathway population before and after self-sealing

Results:

- **Pathway formation is by creating dilatant pathways instead of fracture formation** Gas entry occurs at a pressure considerably **below the stress imposed**, therefore gas pathways are not traditional fractures
- The **distribution** of pathways is **stochastic**
- Multiple pathways form at the same time
- Some pathways paused in their growth and restarted to grow later
- **Walls of a dilatant pathway elastically compress** to accommodate the pathway
- **Water content controls the width and velocity of pathway propagation**
- **Self-sealing was observed, with a secondary set of pathways forming that did not correspond with the primary features**

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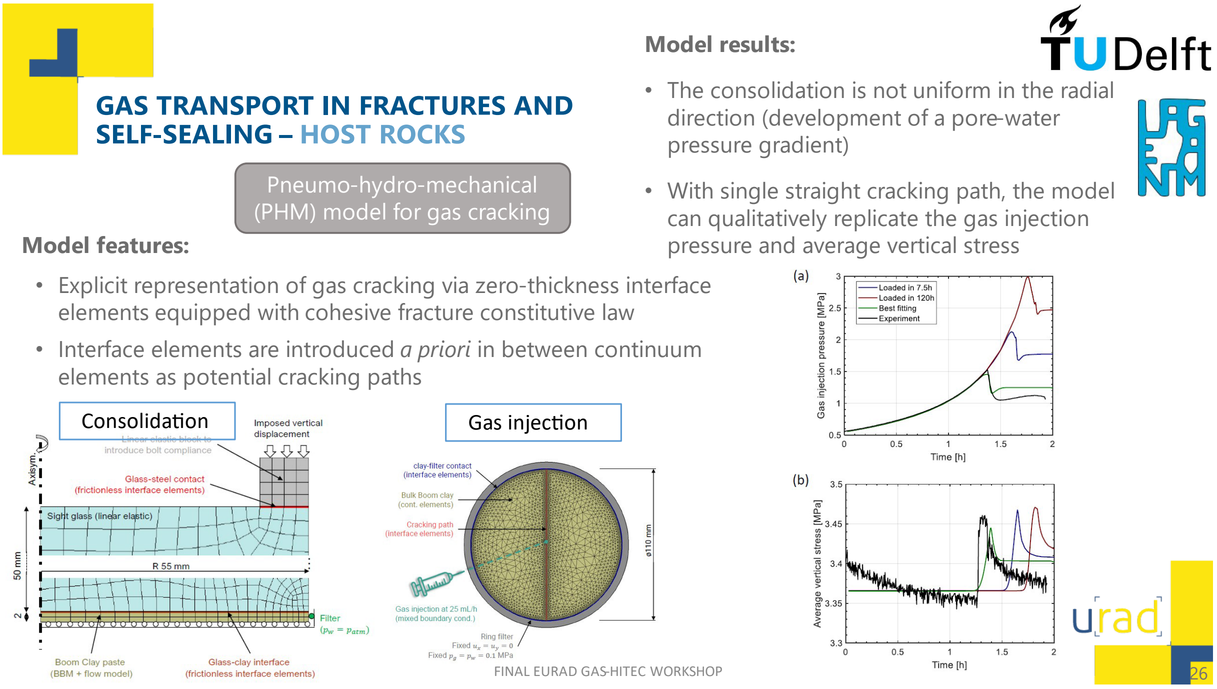

GAS TRANSPORT IN FRACTURES AND SELF-SEALING – HOST ROCKS

Pneumo-hydro-mechanical (PHM) model for gas cracking

Model features:

- Explicit representation of gas cracking via zero-thickness interface elements equipped with cohesive fracture constitutive law
- Interface elements are introduced *a priori* in between continuum elements as potential cracking paths

Consolidation

Gas injection

Model results:

- The consolidation is not uniform in the radial direction (development of a pore-water pressure gradient)
- With single straight cracking path, the model can qualitatively replicate the gas injection pressure and average vertical stress

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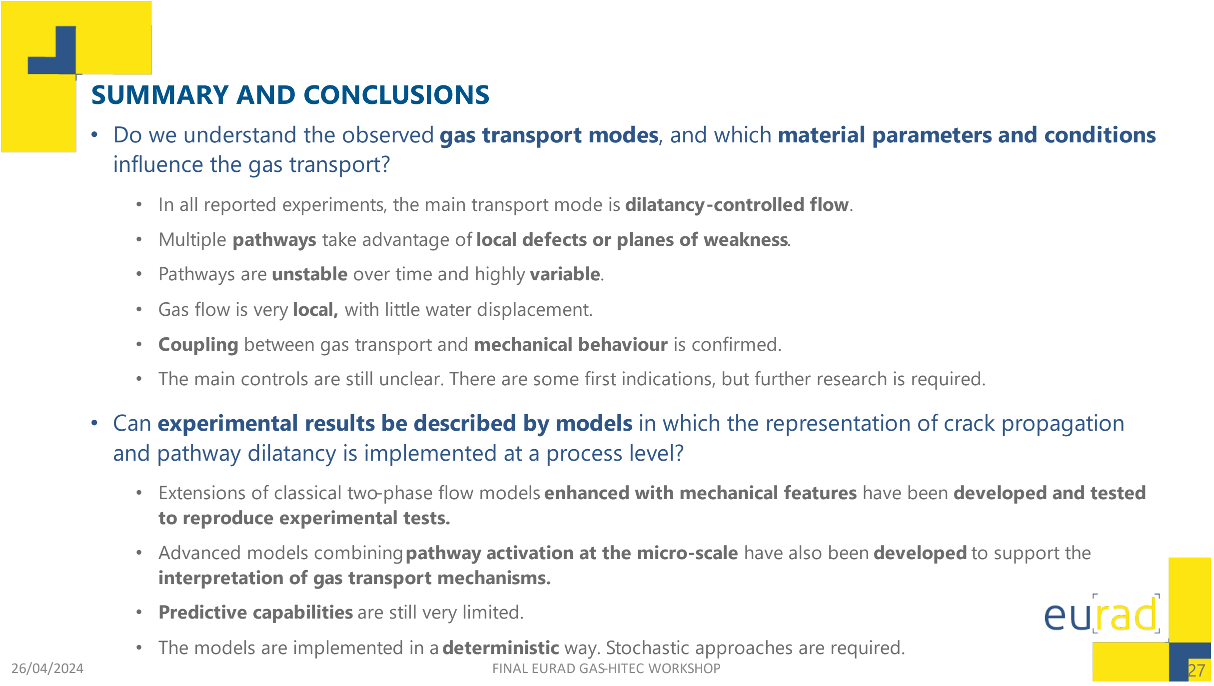

SUMMARY AND CONCLUSIONS

- Do we understand the observed **gas transport modes**, and which **material parameters and conditions** influence the gas transport?
  - In all reported experiments, the main transport mode is **dilatancy-controlled flow**.
  - Multiple **pathways** take advantage of **local defects or planes of weakness**.
  - Pathways are **unstable** over time and highly **variable**.
  - Gas flow is very **local,** with little water displacement.
  - **Coupling** between gas transport and **mechanical behaviour** is confirmed.
  - The main controls are still unclear. There are some first indications, but further research is required.
- Can **experimental results be described by models** in which the representation of crack propagation and pathway dilatancy is implemented at a process level?
  - Extensions of classical two-phase flow models **enhanced with mechanical features** have been **developed and tested to reproduce experimental tests.**
  - Advanced models combining **pathway activation at the micro-scale** have also been **developed** to support the **interpretation of gas transport mechanisms.**
  - **Predictive capabilities** are still very limited.
  - The models are implemented in a **deterministic** way. Stochastic approaches are required.

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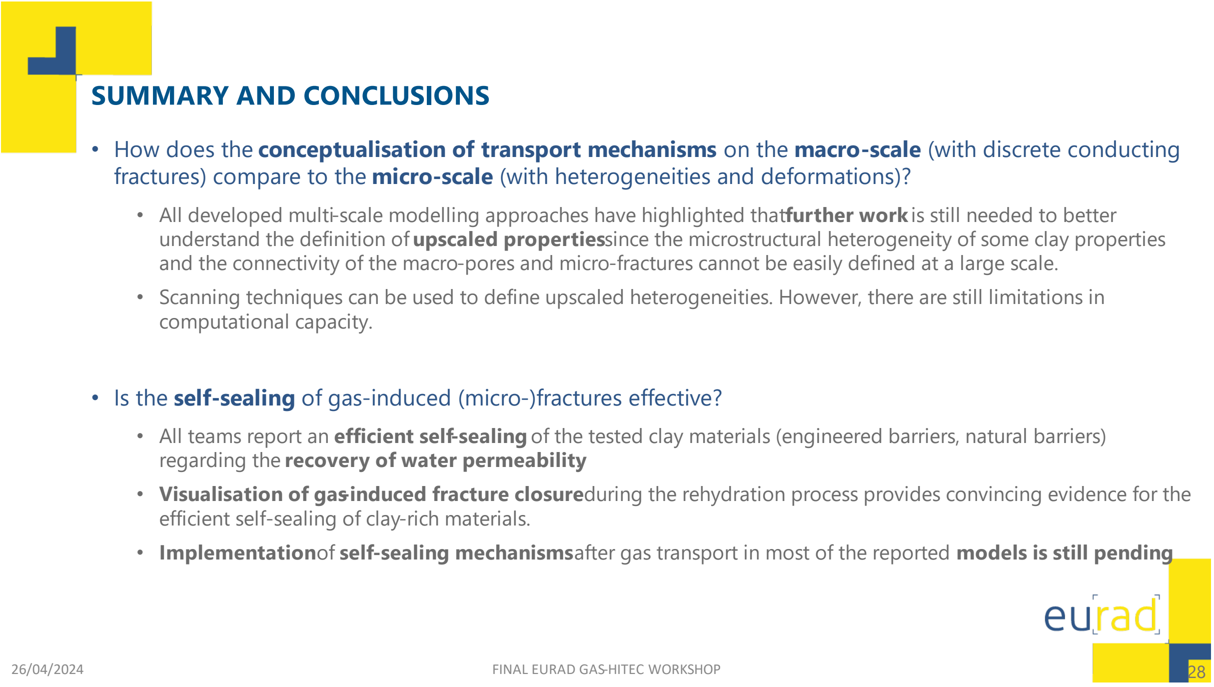

SUMMARY AND CONCLUSIONS

- How does the **conceptualisation of transport mechanisms** on the **macro-scale** (with discrete conducting fractures) compare to the **micro-scale** (with heterogeneities and deformations)?
  - All developed multi-scale modelling approaches have highlighted that **further work** is still needed to better understand the definition of **upscaled properties** since the microstructural heterogeneity of some clay properties and the connectivity of the macro-pores and micro-fractures cannot be easily defined at a large scale.
  - Scanning techniques can be used to define upscaled heterogeneities. However, there are still limitations in computational capacity.
- Is the **self-sealing** of gas-induced (micro-)fractures effective?
  - All teams report an **efficient self-sealing** of the tested clay materials (engineered barriers, natural barriers) regarding the **recovery of water permeability**
  - **Visualisation of gas-induced fracture closure** during the rehydration process provides convincing evidence for the efficient self-sealing of clay-rich materials.
  - **Implementation** of **self-sealing mechanisms** after gas transport in most of the reported **models is still pending**

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THANK YOU FOR YOUR ATTENTION!

Session 3: Messages to end-users: Input of EURAD-GAS and EURAD-HITEC to the repository design and the safety case

3.1 Key messages for treatment of high temperature (EURAD-HITEC)

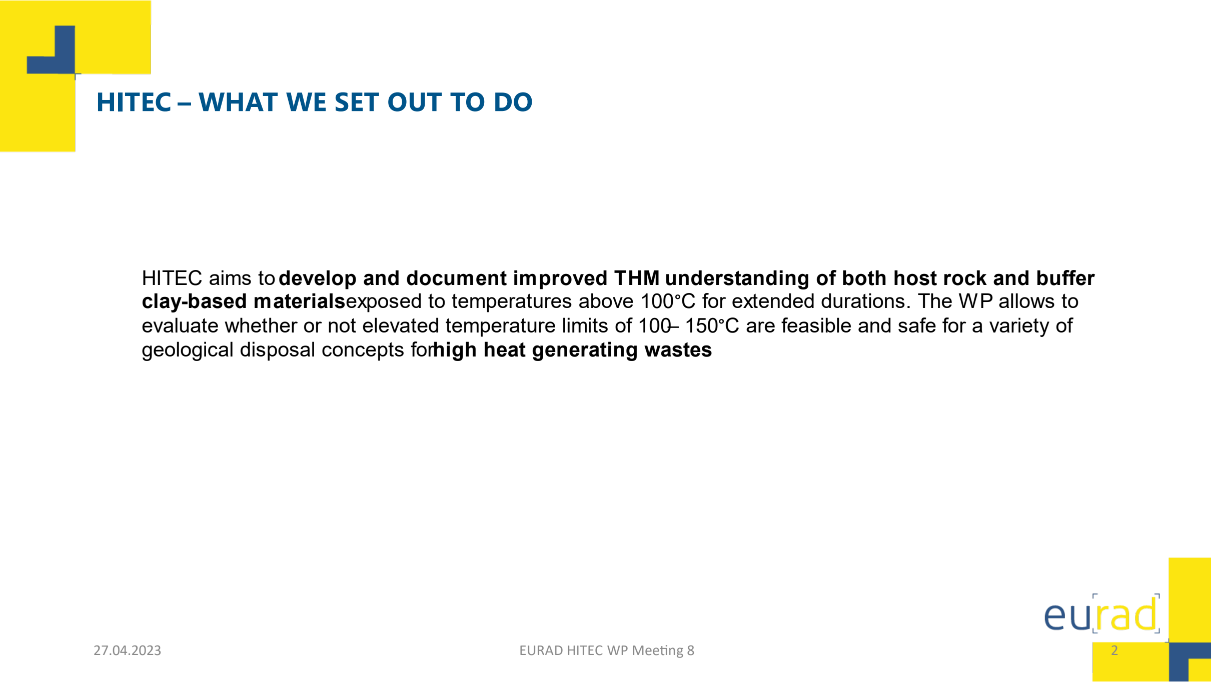
eurad
European Joint Programme on Radioactive Waste Management

KEY MESSAGES FOR TREATMENT OF HITEC

Safety Case and Repository Design Guidance

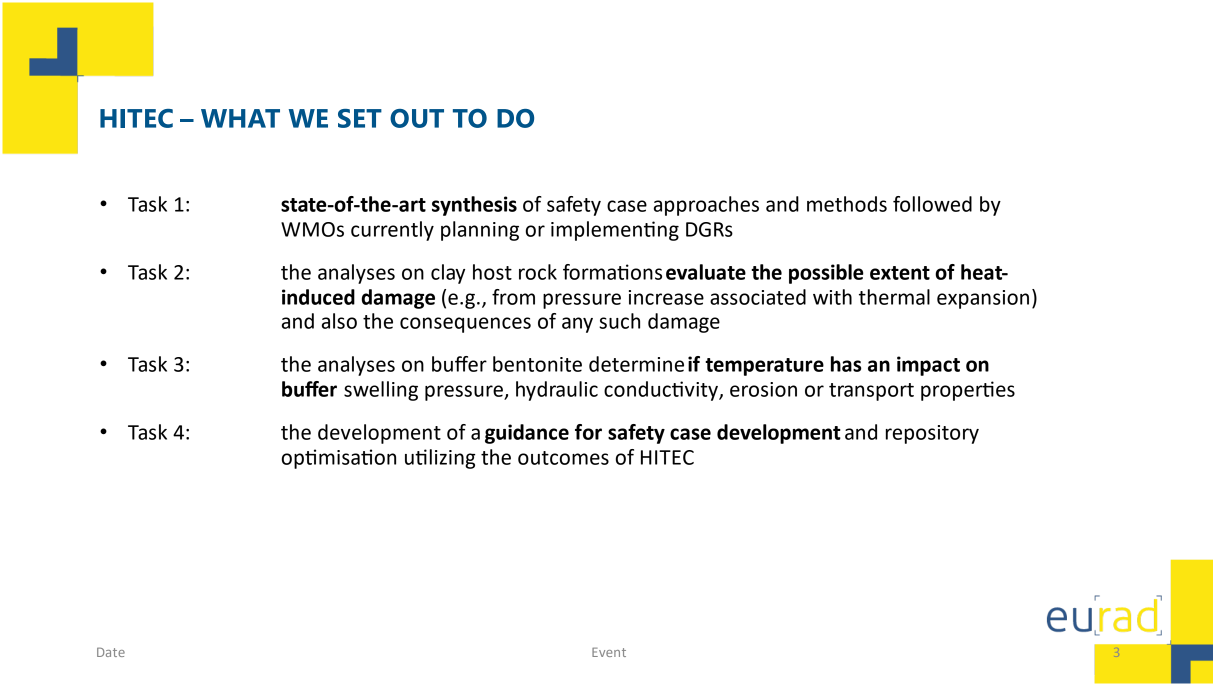
26.04.2024 • Olivier Leupin & Alexandros Papafotiou

This project has received funding from the European Union's Horizon 2020 research and innovation programme 2014 -2018 under grant agreement N°847593



HITEC – WHAT WE SET OUT TO DO

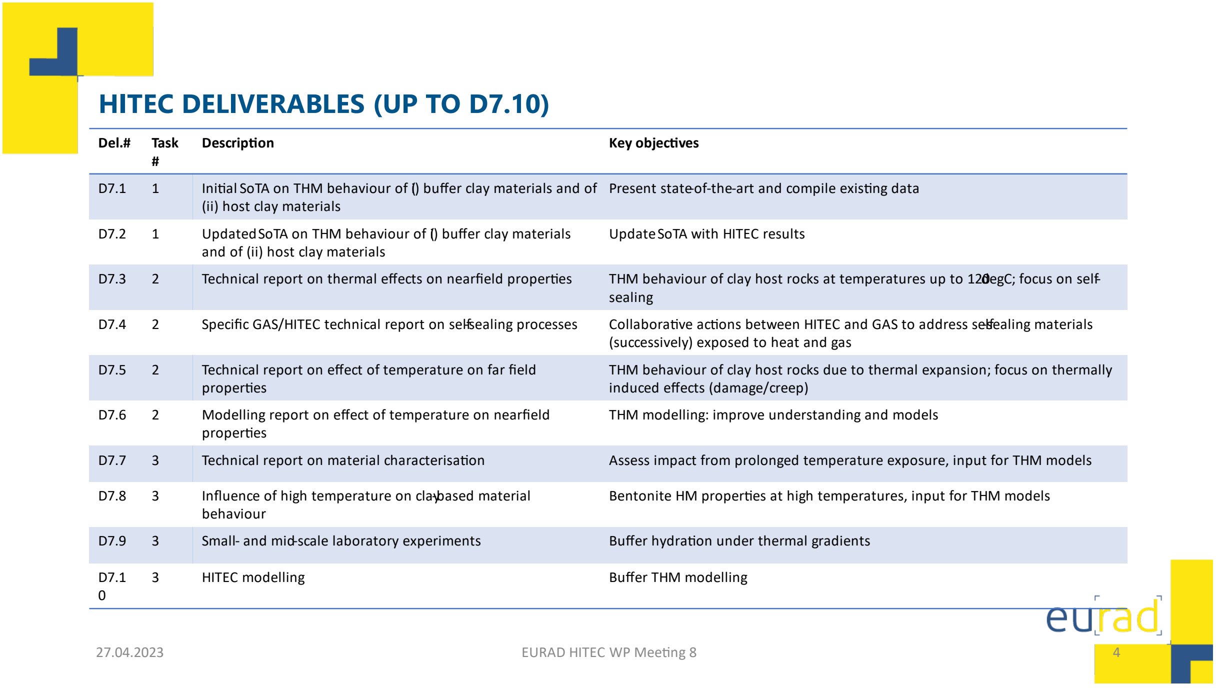
HITEC aims to **develop and document improved THM understanding of both host rock and buffer clay-based materials** exposed to temperatures above 100°C for extended durations. The WP allows to evaluate whether or not elevated temperature limits of 100– 150°C are feasible and safe for a variety of geological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



HITEC – WHAT WE SET OUT TO DO

- Task 1: **state-of-the-art synthesis** of safety case approaches and methods followed by WMOs currently planning or implementing DGRs
- Task 2: the analyses on clay host rock formations **evaluate the possible extent of heat-induced damage** (e.g., from pressure increase associated with thermal expansion) and also the consequences of any such damage
- Task 3: the analyses on buffer bentonite determine **if temperature has an impact on buffer** swelling pressure, hydraulic conductivity, erosion or transport properties
- Task 4: the development of a **guidance for safety case development** and repository optimisation utilizing the outcomes of HITEC

Date Event 3



HITEC DELIVERABLES (UP TO D7.10)

Del.#	Task #	Description	Key objectives
D7.1	1	Initial SoTA on THM behaviour of (i) buffer clay materials and of (ii) host clay materials	Present state-of-the-art and compile existing data
D7.2	1	Updated SoTA on THM behaviour of (i) buffer clay materials and of (ii) host clay materials	Update SoTA with HITEC results
D7.3	2	Technical report on thermal effects on nearfield properties	THM behaviour of clay host rocks at temperatures up to 120 degC; focus on self-sealing
D7.4	2	Specific GAS/HITEC technical report on self-sealing processes	Collaborative actions between HITEC and GAS to address self-sealing materials (successively) exposed to heat and gas
D7.5	2	Technical report on effect of temperature on far field properties	THM behaviour of clay host rocks due to thermal expansion; focus on thermally induced effects (damage/creep)
D7.6	2	Modelling report on effect of temperature on nearfield properties	THM modelling: improve understanding and models
D7.7	3	Technical report on material characterisation	Assess impact from prolonged temperature exposure, input for THM models
D7.8	3	Influence of high temperature on clay-based material behaviour	Bentonite HM properties at high temperatures, input for THM models
D7.9	3	Small- and mid-scale laboratory experiments	Buffer hydration under thermal gradients
D7.10	3	HITEC modelling	Buffer THM modelling

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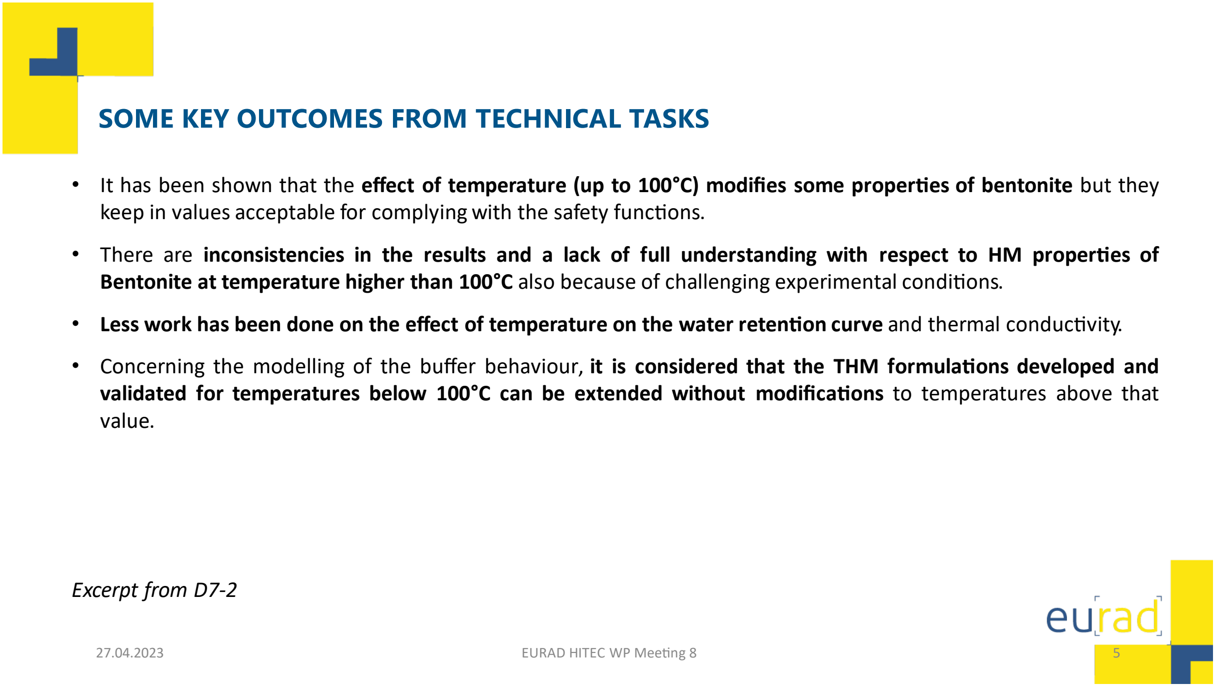

SOME KEY OUTCOMES FROM TECHNICAL TASKS

- 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.

Excerpt from D7-2

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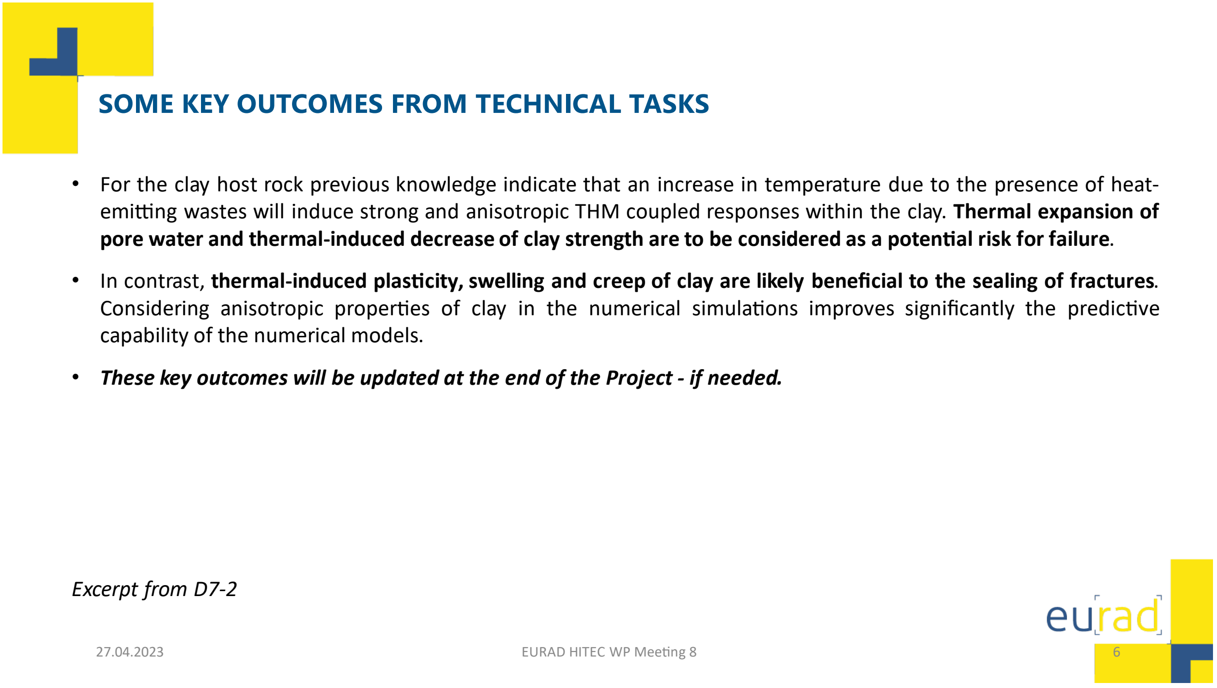

SOME KEY OUTCOMES FROM TECHNICAL TASKS

- 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.
- ***These key outcomes will be updated at the end of the Project - if needed.***

Excerpt from D7-2

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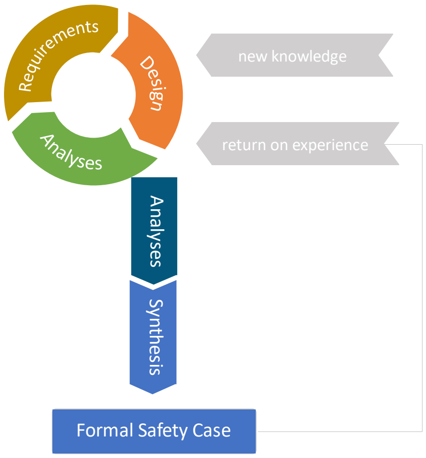
WHAT DO THESE OUTCOMES MEAN FOR THE SAFETY OF A DGR?

- What is a safety case?
  - «*The synthesis of* evidence and arguments gathered, and analyses carried out, in the course of safety assessment to make the case for the post-closure safety of a disposal system.* »
- What is the safety assessment?
  - « Safety assessment is ***the process of*** *gathering the evidence and arguments and carrying out analyses regarding the safety of the disposal system during the post-closure phase and is the means by which the safety case is developed.* »
- Safety assessement ususally includes following aspects:
  - A systematic approach to information gathering and integration
  - **Rigour in consideration and treatment of uncertainty**
  - Assurance of completeness
  - Development, validation and verification of models and databases
  - Use of stylised approaches
  - Multiple lines of arguments for safety
  - Internal and external reviews
  - Etc.

WHAT DO THESE OUTCOMES MEAN FOR THE POST-CLOSURE SAFETY?

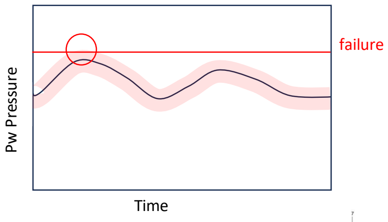


- Safety assessments form a central part for the safety case for a given project milestone e.g. general license
- Safety assessments may also occur in the iterative development process, as part of system analyses
- The **link** of attributed **safety function, performance and to requirements is essential**– the goal being to demonstrate that the requirements are met.

E.G. PERFORMANCE ASSESSMENT WITH REGARD TO THERMAL FRACTURES

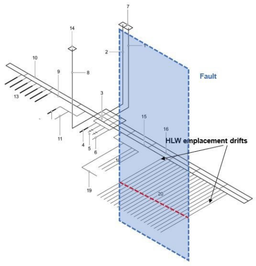
Thermal evolution with a set of parameters in performance assessment:

①



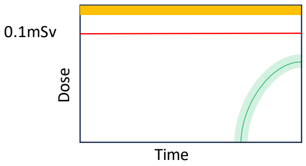
②

Development of a safety assessment scenario:



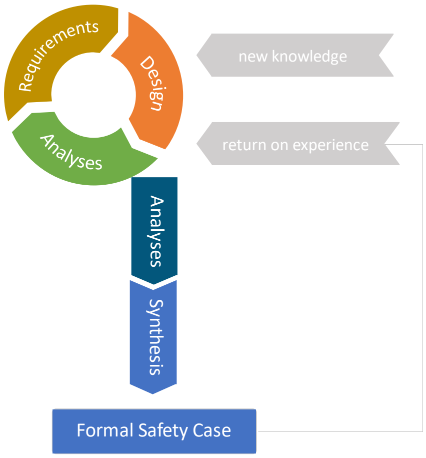
③

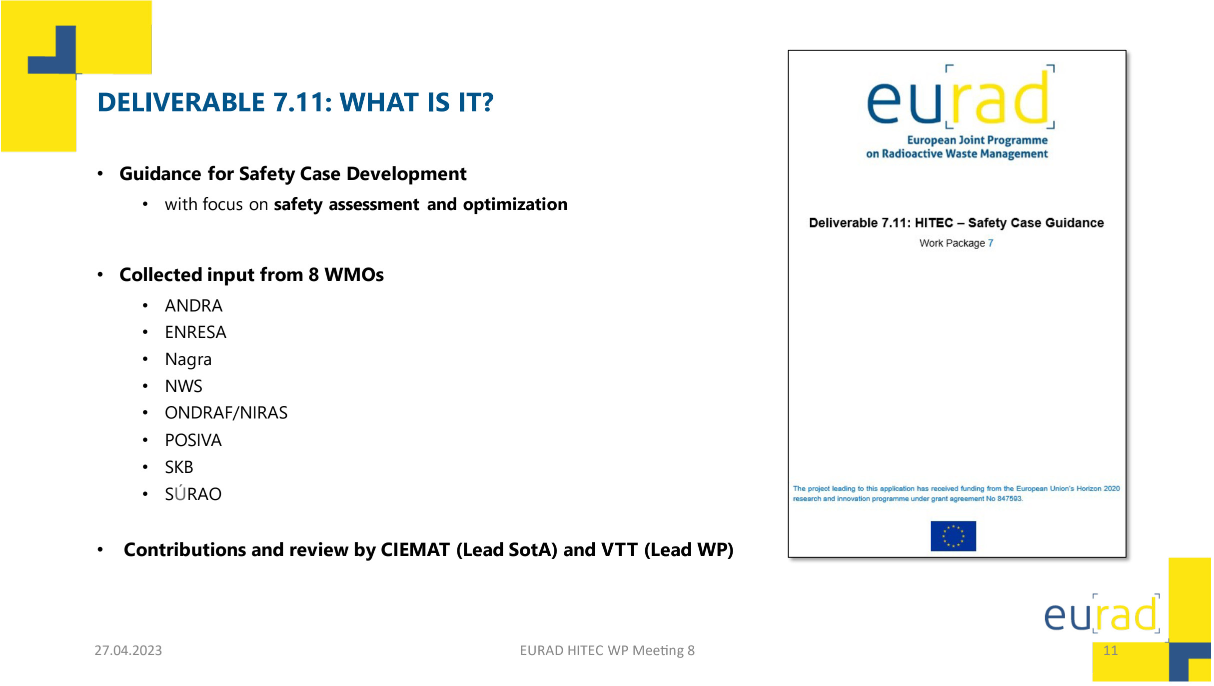
Radiological consequence of a thermal fracture:



WHAT DO THESE OUTCOMES MEAN FOR THE SAFETY OF A DGR?

- If safety related requirements are not satisfied the design needs to be re-assessed.
  - With regard to the loss of integrity of one or more barriers due to thermal impact following changes to the design can be considered: change pitch, loading of canisters, drift geometries, repository layout, host rock etc.
- **A good repository design basis includes resilience towards repository induced effects** such that it can account for large uncertainties with respect to barrier performance.


Requirements
Design
Analyses
new knowledge
return on experience
Analyses
Synthesis
Formal Safety Case



DELIVERABLE 7.11: WHAT IS IT?

- **Guidance for Safety Case Development**
  - with focus on **safety assessment and optimization**

- **Collected input from 8 WMOs**
  - ANDRA
  - ENRESA
  - Nagra
  - NWS
  - ONDRAF/NIRAS
  - POSIVA
  - SKB
  - SÚRAO

- **Contributions and review by CIEMAT (Lead SotA) and VTT (Lead WP)**

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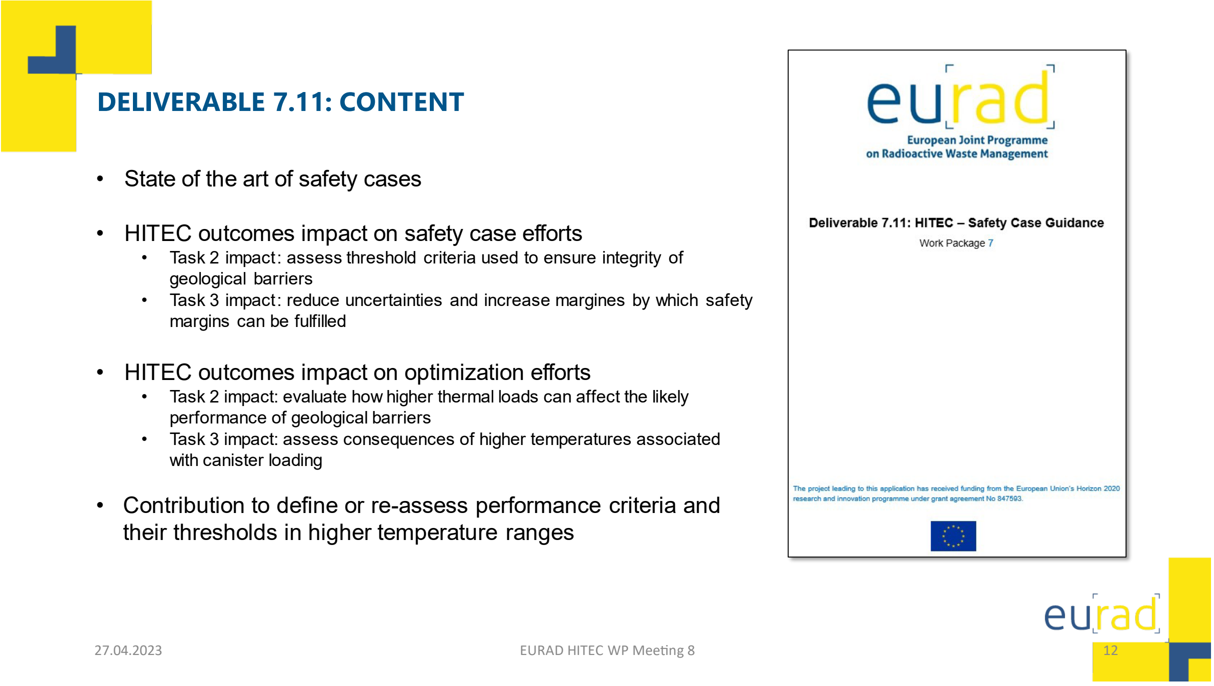
Deliverable 7.11: HITEC – Safety Case Guidance
Work Package 7

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.



DELIVERABLE 7.11: CONTENT

- State of the art of safety cases

- HITEC outcomes impact on safety case efforts
  - Task 2 impact: assess threshold criteria used to ensure integrity of geological barriers
  - Task 3 impact: reduce uncertainties and increase margines by which safety margins can be fulfilled

- HITEC outcomes impact on optimization efforts
  - Task 2 impact: evaluate how higher thermal loads can affect the likely performance of geological barriers
  - Task 3 impact: assess consequences of higher temperatures associated with canister loading

- Contribution to define or re-assess performance criteria and their thresholds in higher temperature ranges

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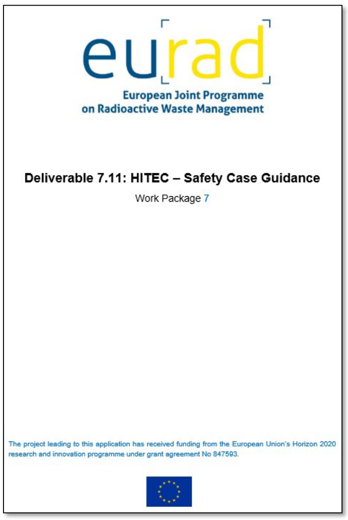
DELIVERABLE 7.11: DOCUMENT STRUCTURE

- **Introduction w. background HITEC project**
- **WMOs safety case overviews**
  - WMO-1
  - WMO-2
  - …
- **Impact of improved understanding on safety cases**
  - HITEC project results impact in relation to WMO-1 safety case
  - HITEC project results impact in relation to WMO-2 safety case
  - …
  - ➢ different outcomes depending on each programme!
- **Summary & Conclusions**



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Deliverable 7.11: HITEC – Safety Case Guidance
Work Package 7

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

KEY MESSAGES FROM WMO'S IN D7.11

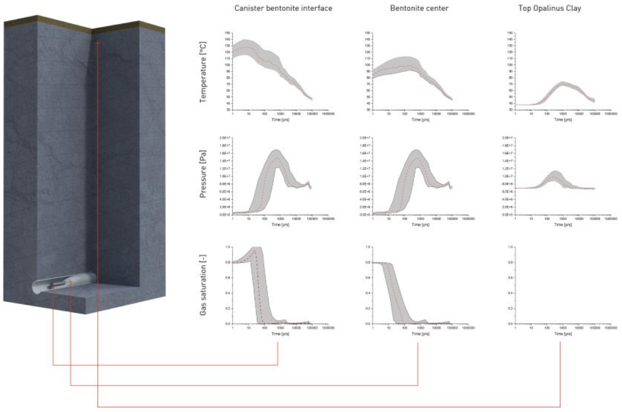
- **ANDRA:** The laboratory experiments performed in the framework of the EURAD HITEC project **confirmed that the Callovo-Oxfordian claystone keeps its favourable mechanical and retention properties**, even when heated at high temperature (up to 100°C).
- **ENRESA:** The experimental evidence from the HITEC […], related to the thermal induced effects of both the clay host rock and the bentonite buffer for temperatures above 100°C, **provides important input** to the existing evidence basis and could contribute **to further refinements and considerations** in the safety assessment of the repository. Furthermore, evidence from the HITEC project will support the optimisation of the repository at a later stage.
- **NAGRA:** It is […] **essential to understand the processes** that could occur during the thermal transient phase. This will **allow an appropriated optimisation of the repository and its components**
- **NWS:** The **results of HITEC** provide fundamental underpinning of the UK safety case should a Jurassic clay host rock be selected, and provide an initial indication that a thermal limit on LSSR of 90°C is acceptable (depending on site-specific conditions). This **allows for optimisation of the GDF footprint**, should bentonite be shown to meet its safety functions at temperatures greater than 100°C […]

KEY MESSAGES FROM WMO'S IN D7.11

- **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

SUMMARY AND CONCLUSION

- The **strength and reliability** of the evidence provided **hinge upon its capacity to accurately represent the anticipated conditions** within a geological repository.
- Therefore, it is essential to establish a **well-constrained evolutionary path** ("storyboard") for thermal, hydraulic, and mechanical (THM) conditions before specifying the parameters for testing.
- **By gaining a comprehensive understanding of the evolution of safety-related properties** in both technical and natural barriers, **we can reduce unnecessary conservatisms and allow for optimizations** for various aspects of the repository, from individual components to the layout of the entire facility.



3.2 Key messages for treatment of gas transport (EURAD-GAS)

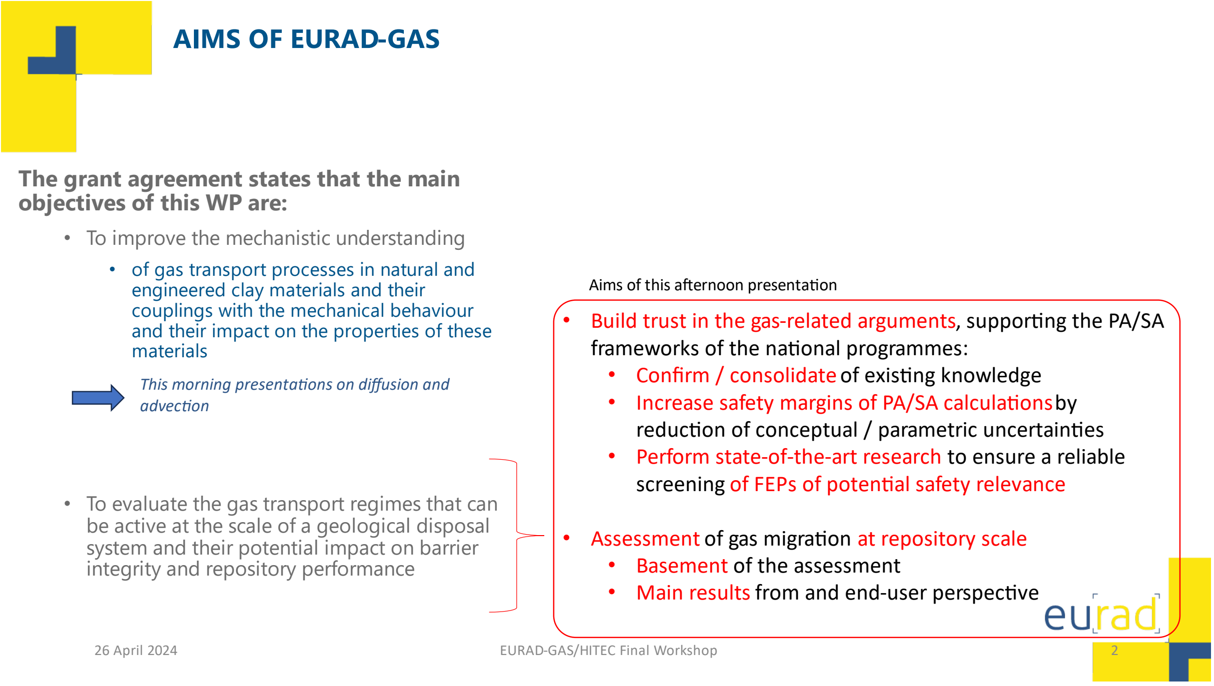
EURAD GAS-HITEC FINAL WORKSHOP

WP GAS : KEY MESSAGES FOR TREATMENT OF GAS TRANSPORT: A PA/SA PERSPECTIVE

Paul Marschall, Nagra
Jacques Wendling, Andra

26 April 2024

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n° 847593.



AIMS OF EURAD-GAS

The grant agreement states that the main objectives of this WP are:

- To improve the mechanistic understanding
  - of gas transport processes in natural and engineered clay materials and their couplings with the mechanical behaviour and their impact on the properties of these materials

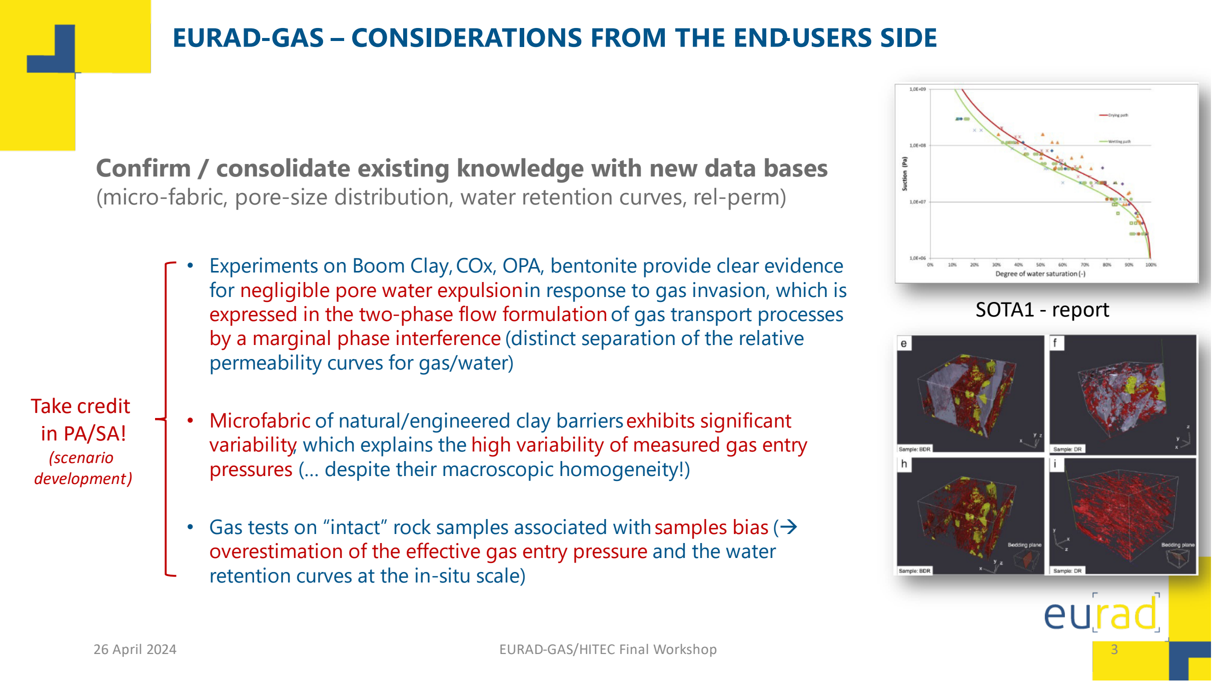
→ *This morning presentations on diffusion and advection*

- To evaluate the gas transport regimes that can be active at the scale of a geological disposal system and their potential impact on barrier integrity and repository performance

Aims of this afternoon presentation

- Build trust in the gas-related arguments, supporting the PA/SA frameworks of the national programmes:
  - Confirm / consolidate of existing knowledge
  - Increase safety margins of PA/SA calculations by reduction of conceptual / parametric uncertainties
  - Perform state-of-the-art research to ensure a reliable screening of FEPs of potential safety relevance
- Assessment of gas migration at repository scale
  - Basement of the assessment
  - Main results from and end-user perspective

26 April 2024 EURAD-GAS/HITEC Final Workshop 2



EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

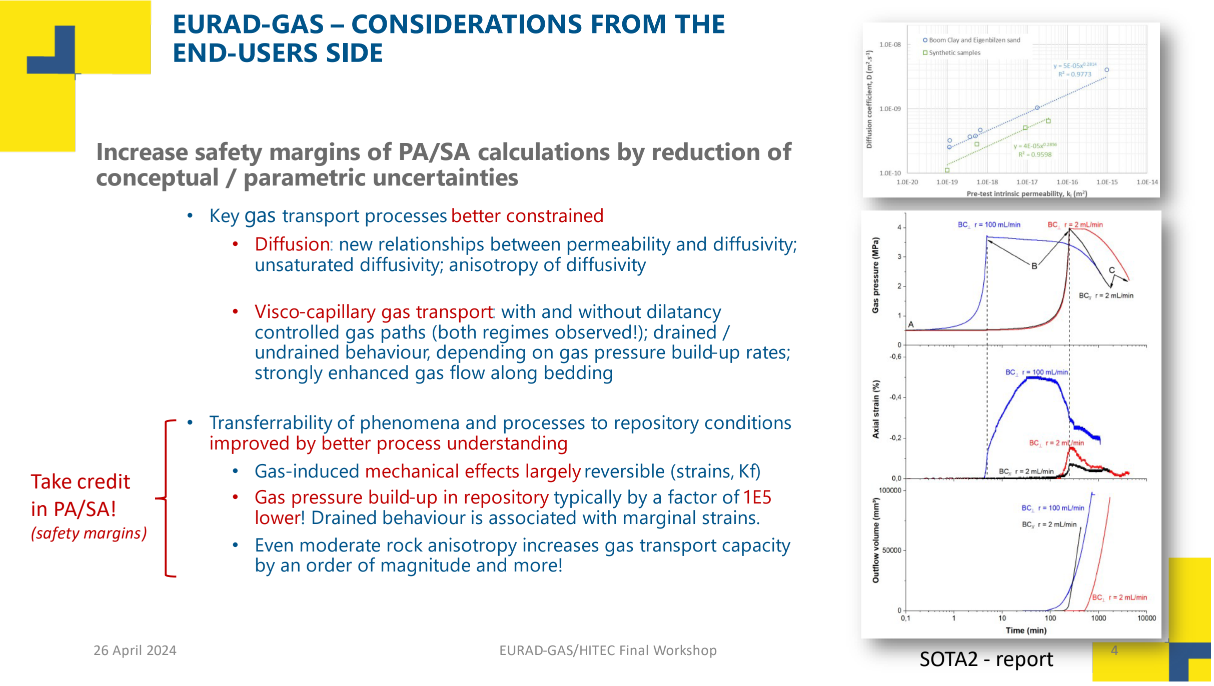
Confirm / consolidate existing knowledge with new data bases
(micro-fabric, pore-size distribution, water retention curves, rel-perm)

Take credit in PA/SA!
(scenario development)

- Experiments on Boom Clay, COx, OPA, bentonite provide clear evidence for negligible pore water expulsion in response to gas invasion, which is expressed in the two-phase flow formulation of gas transport processes by a marginal phase interference (distinct separation of the relative permeability curves for gas/water)
- Microfabric of natural/engineered clay barriers exhibits significant variability, which explains the high variability of measured gas entry pressures (… despite their macroscopic homogeneity!)
- Gas tests on “intact” rock samples associated with samples bias (→ overestimation of the effective gas entry pressure and the water retention curves at the in-situ scale)

SOTA1 - report

26 April 2024 EURAD-GAS/HITEC Final Workshop 3



EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Increase safety margins of PA/SA calculations by reduction of conceptual / parametric uncertainties

- Key gas transport processes better constrained
  - Diffusion: new relationships between permeability and diffusivity; unsaturated diffusivity; anisotropy of diffusivity
  - Visco-capillary gas transport: with and without dilatancy controlled gas paths (both regimes observed!); drained / undrained behaviour, depending on gas pressure build-up rates; strongly enhanced gas flow along bedding
- Transferrability of phenomena and processes to repository conditions improved by better process understanding
  - Gas-induced mechanical effects largely reversible (strains, Kf)
  - Gas pressure build-up in repository typically by a factor of 1E5 lower! Drained behaviour is associated with marginal strains.
  - Even moderate rock anisotropy increases gas transport capacity by an order of magnitude and more!

Take credit in PA/SA!
(safety margins)

SOTA2 - report

26 April 2024 EURAD-GAS/HITEC Final Workshop 4

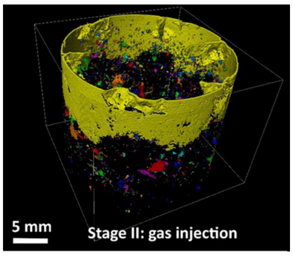
EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Increase safety margins of PA/SA calculations by reduction of conceptual / parametric uncertainties

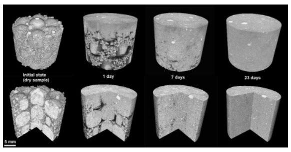
- Gas related interactions in the composite multi-barrier system better constrained
  - Localisation of gas transport paths / material interfaces: new techniques for the visualization of gas transport paths provide insight in prevailing phenomena and processes
  - Selfsealing processes after gas induced failure: new techniques for the visualization of the efficiency of self-sealing

Take credit
in PA/SA!
(safety margins)

- Gas related interactions control total system performance
  - Gas transport occurs along the paths of least resistance!



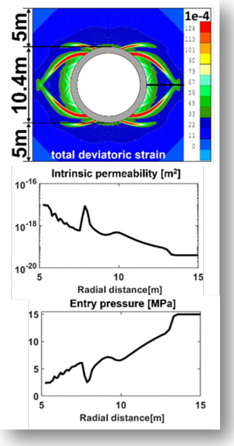
Deliverable 6.8 / IRSN (μ-CT)



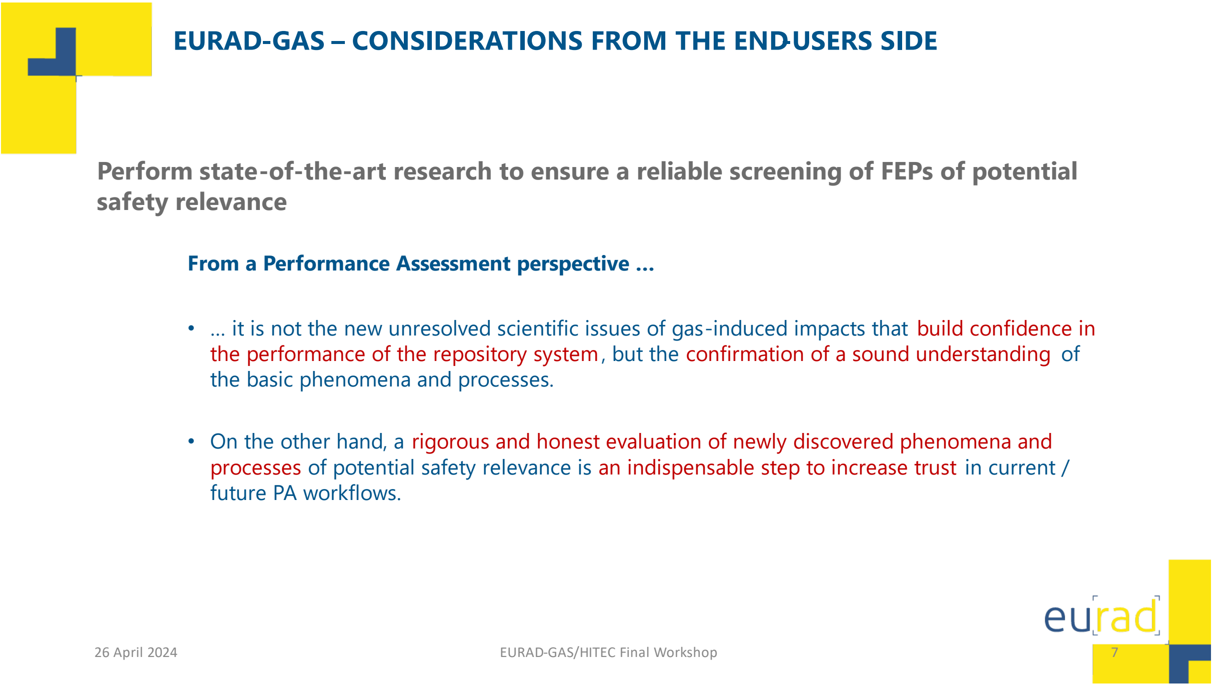
EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Increase safety margins of PA/SA calculations by reduction of conceptual / parametric uncertainties

- Tremendous progress has been made in TH^{2}M-process modelling
  - Model identification and parameter estimation: Advanced TH^{2}M frameworks for back analyses of lab/field tests
  - Uncertainty quantitification associated with model abstraction: validation of TH^{2}M → TH^2 model abstractions at component scale provides confidence ranges at the total system scale.
  - Code verification, model validation and calculation benchmarking: TH^{2}M tool boxes and test cases for building confidence in modelling frameworks



SOTA2 - report



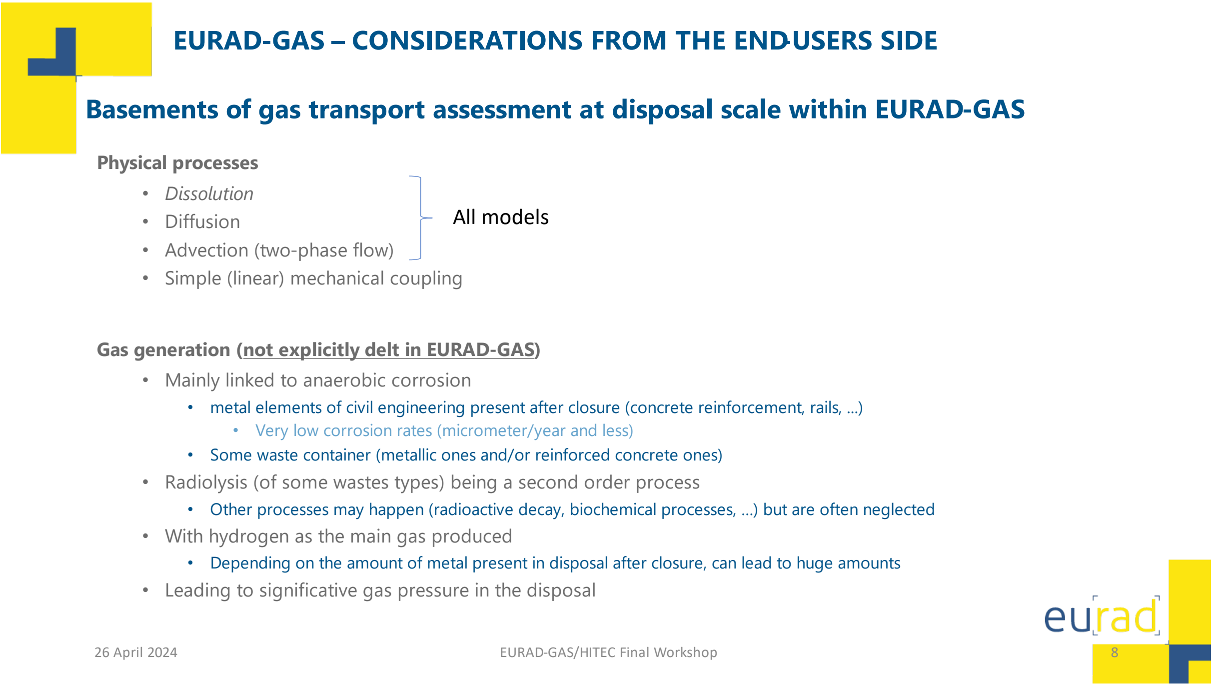
EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Perform state-of-the-art research to ensure a reliable screening of FEPs of potential safety relevance

From a Performance Assessment perspective …

- … it is not the new unresolved scientific issues of gas-induced impacts that build confidence in the performance of the repository system, but the confirmation of a sound understanding of the basic phenomena and processes.
- On the other hand, a rigorous and honest evaluation of newly discovered phenomena and processes of potential safety relevance is an indispensable step to increase trust in current / future PA workflows.

26 April 2024 EURAD-GAS/HITEC Final Workshop 7



EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Basements of gas transport assessment at disposal scale within EURAD-GAS

Physical processes

- *Dissolution*
- Diffusion
- Advection (two-phase flow)
- Simple (linear) mechanical coupling

All models

Gas generation (<u>not explicitly delt in EURAD-GAS</u>)

- Mainly linked to anaerobic corrosion
  - metal elements of civil engineering present after closure (concrete reinforcement, rails, …)
    - Very low corrosion rates (micrometer/year and less)
  - Some waste container (metallic ones and/or reinforced concrete ones)
- Radiolysis (of some wastes types) being a second order process
  - Other processes may happen (radioactive decay, biochemical processes, …) but are often neglected
- With hydrogen as the main gas produced
  - Depending on the amount of metal present in disposal after closure, can lead to huge amounts
- Leading to significative gas pressure in the disposal

26 April 2024 EURAD-GAS/HITEC Final Workshop 8

EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Basements of gas transport assessment at disposal scale within EURAD-GAS

Qualitative conceptualization of gas transport at disposal scale (storyboard) (1/2)

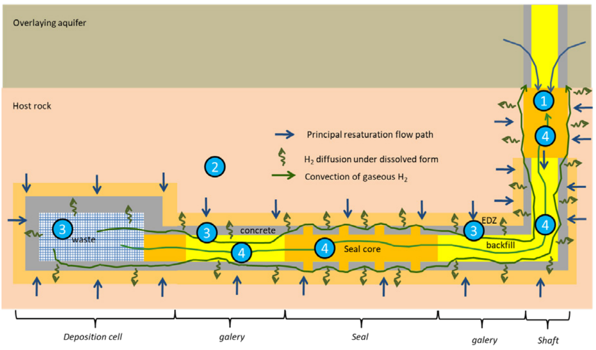
- Space scale involved
  - Gas generation elements (reinforced concrete, wastes, …) are present all over the disposal
  - Hydrogen is a very mobile gas
  - Need to fulfill a global disposal scale assessment
- Time scale involved
  - Previous "disposal scale" assessment (i.e. assessment at least at disposal cell scale) show that due to the very low corrosion rate (micrometer/year and less) the time to reach the gas pressure pick is of several thousands / ten of thousands of years (concept dependent)

EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Basements of gas transport assessment at disposal scale within EURAD-GAS

Qualitative conceptualization of gas transport at disposal scale (storyboard) (1/2)

- A limited number of fundamental drivers
  1. The connection to the surface (shaft seal)
     - Upper aquifer
  2. The gas behavior of the host rock
     - High gas entry pressure
     - Low permeability
     - Low diffusivity
  3. The gas source terms
     - Concrete rebars
     - Waste containers
  4. The gas behavior of the closure system
     - Backfill
     - Seals



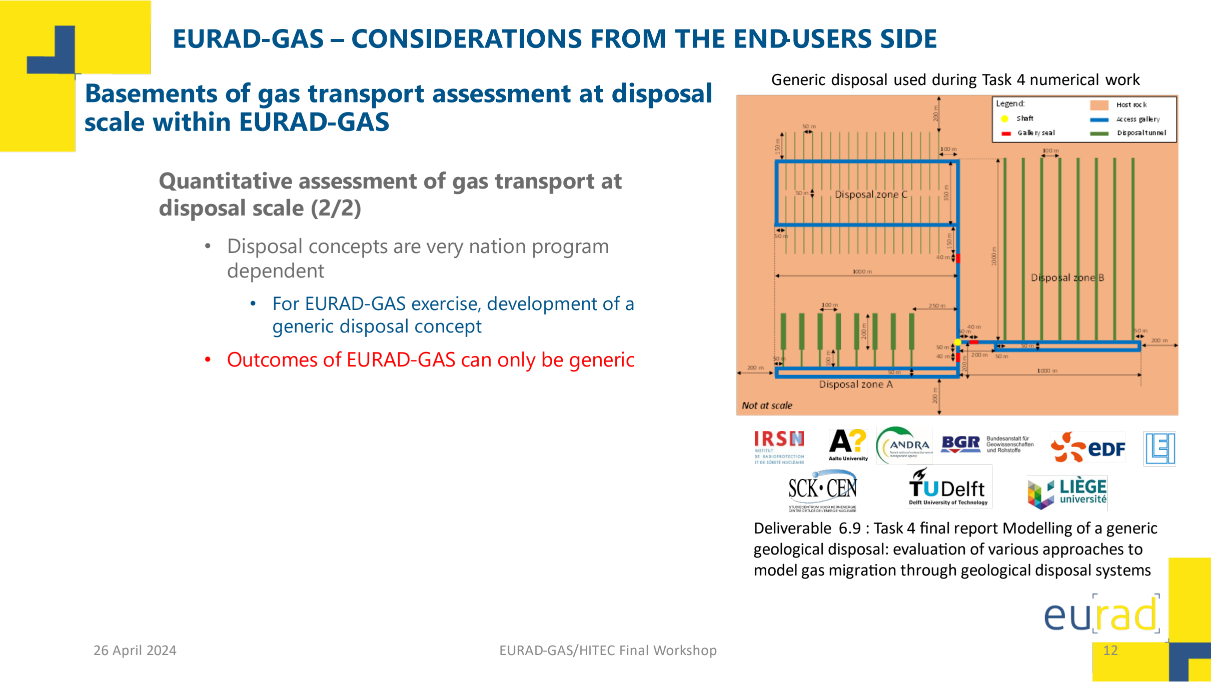
EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Basements of gas transport assessment at disposal scale within EURAD-GAS

Quantitative assessment of gas transport at disposal scale (1/2)

- Space and time scales involved implies the use of numerical simulations
- Development of a mesh at disposal scale
  - Need to define geometrical simplifications
- Limitation on use of mechanical coupling
  - High non linearities
- Limitation on radionuclides transfer
  - Need to dispose of two-phase flow parameters (diffusion coefficient)

These model abstractions can be validated through benchmarking



EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

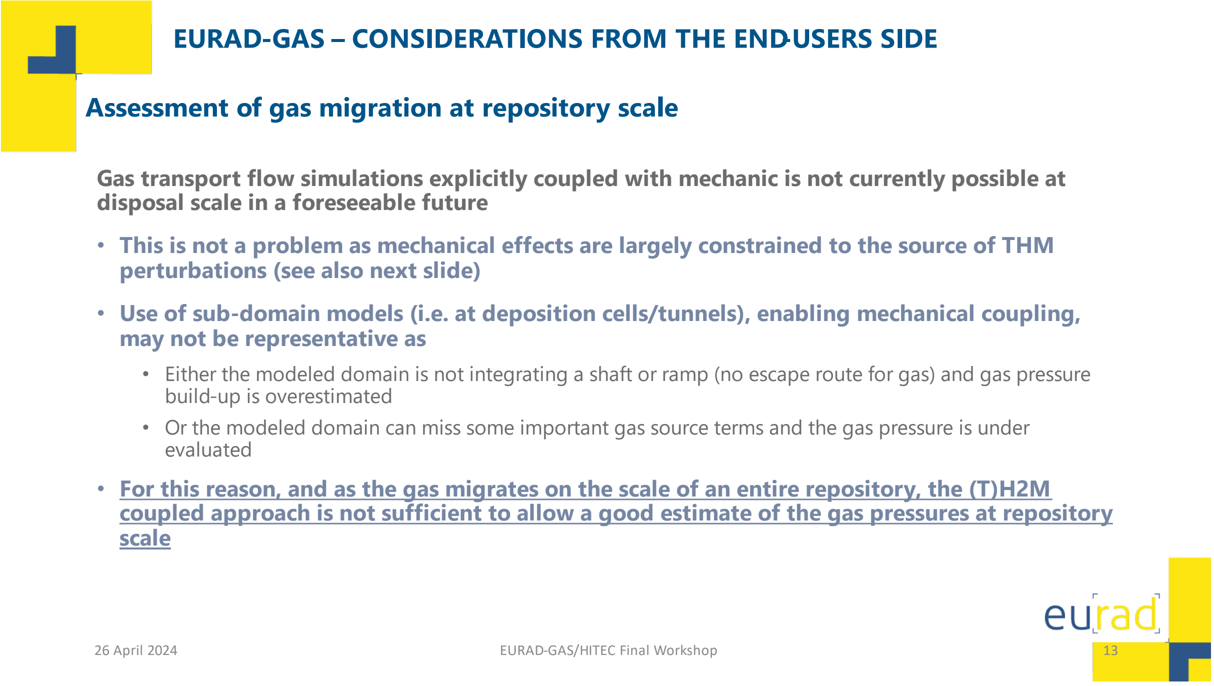
Basements of gas transport assessment at disposal scale within EURAD-GAS

Quantitative assessment of gas transport at disposal scale (2/2)

- Disposal concepts are very nation program dependent
  - For EURAD-GAS exercise, development of a generic disposal concept
- Outcomes of EURAD-GAS can only be generic

Generic disposal used during Task 4 numerical work

Deliverable 6.9 : Task 4 final report Modelling of a generic geological disposal: evaluation of various approaches to model gas migration through geological disposal systems

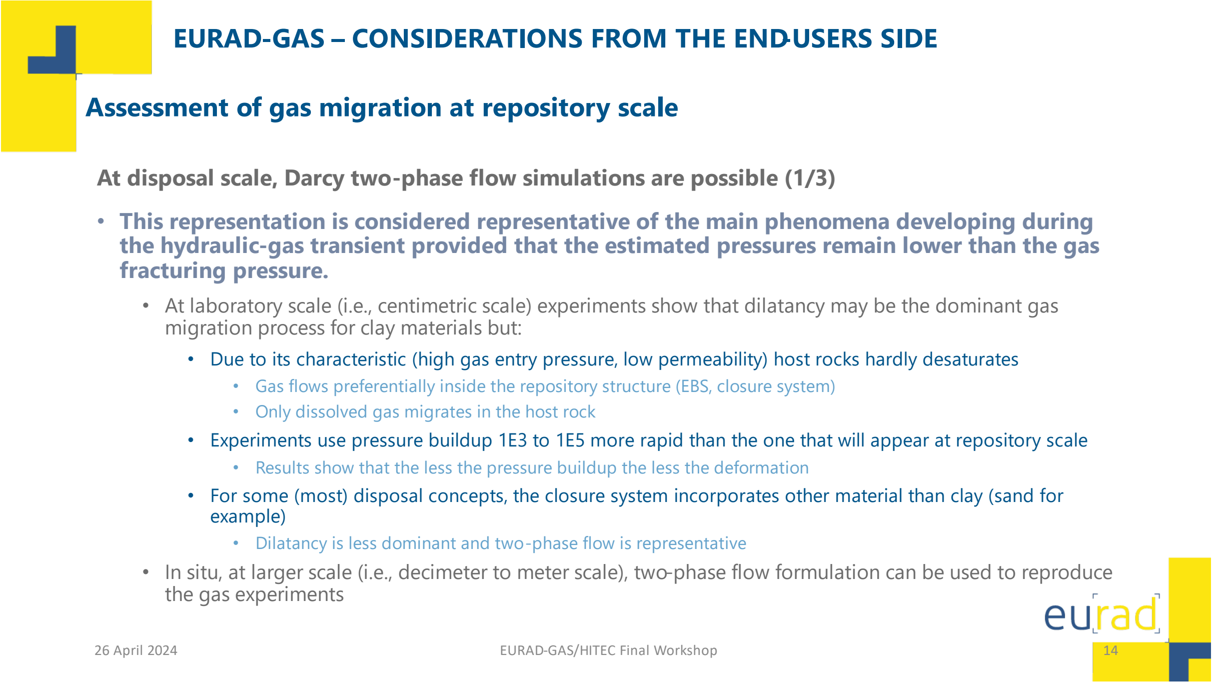


EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Assessment of gas migration at repository scale

Gas transport flow simulations explicitly coupled with mechanic is not currently possible at disposal scale in a foreseeable future

- **This is not a problem as mechanical effects are largely constrained to the source of THM perturbations (see also next slide)**
- **Use of sub-domain models (i.e. at deposition cells/tunnels), enabling mechanical coupling, may not be representative as**
    - Either the modeled domain is not integrating a shaft or ramp (no escape route for gas) and gas pressure build-up is overestimated
    - Or the modeled domain can miss some important gas source terms and the gas pressure is under evaluated
- **For this reason, and as the gas migrates on the scale of an entire repository, the (T)H2M coupled approach is not sufficient to allow a good estimate of the gas pressures at repository scale**

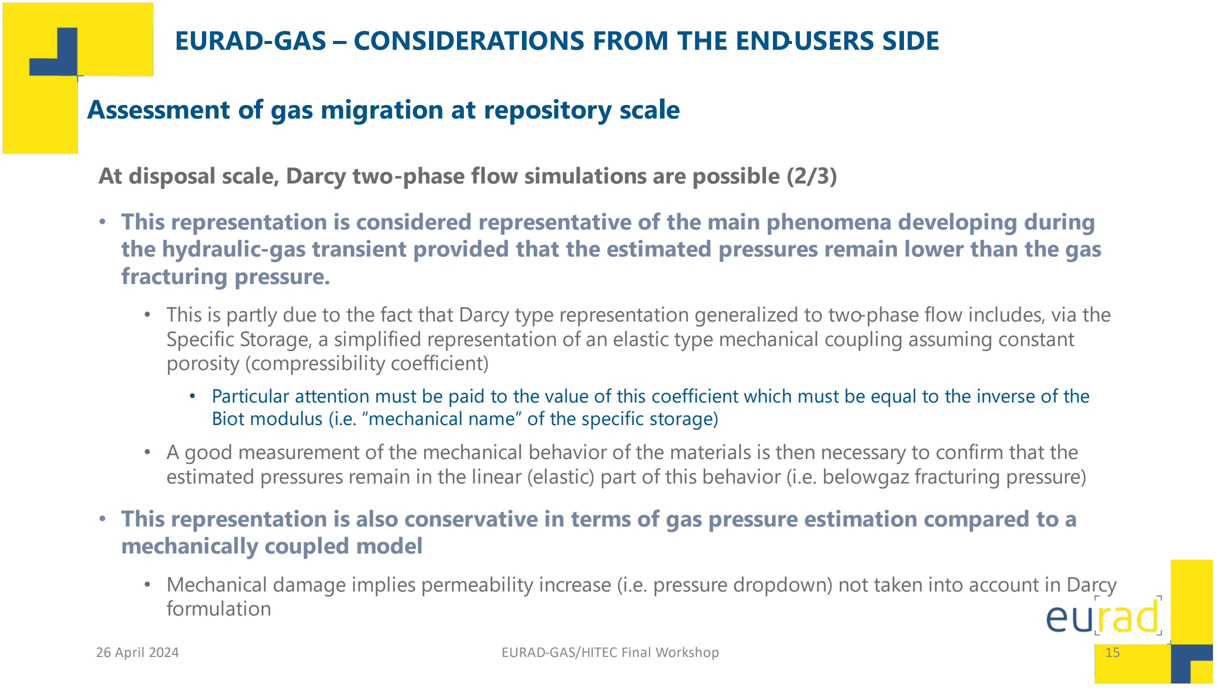


EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Assessment of gas migration at repository scale

At disposal scale, Darcy two-phase flow simulations are possible (1/3)

- **This representation is considered representative of the main phenomena developing during the hydraulic-gas transient provided that the estimated pressures remain lower than the gas fracturing pressure.**
    - At laboratory scale (i.e., centimetric scale) experiments show that dilatancy may be the dominant gas migration process for clay materials but:
        - Due to its characteristic (high gas entry pressure, low permeability) host rocks hardly desaturates
            - Gas flows preferentially inside the repository structure (EBS, closure system)
            - Only dissolved gas migrates in the host rock
        - Experiments use pressure buildup 1E3 to 1E5 more rapid than the one that will appear at repository scale
            - Results show that the less the pressure buildup the less the deformation
        - For some (most) disposal concepts, the closure system incorporates other material than clay (sand for example)
            - Dilatancy is less dominant and two-phase flow is representative
    - In situ, at larger scale (i.e., decimeter to meter scale), two-phase flow formulation can be used to reproduce the gas experiments

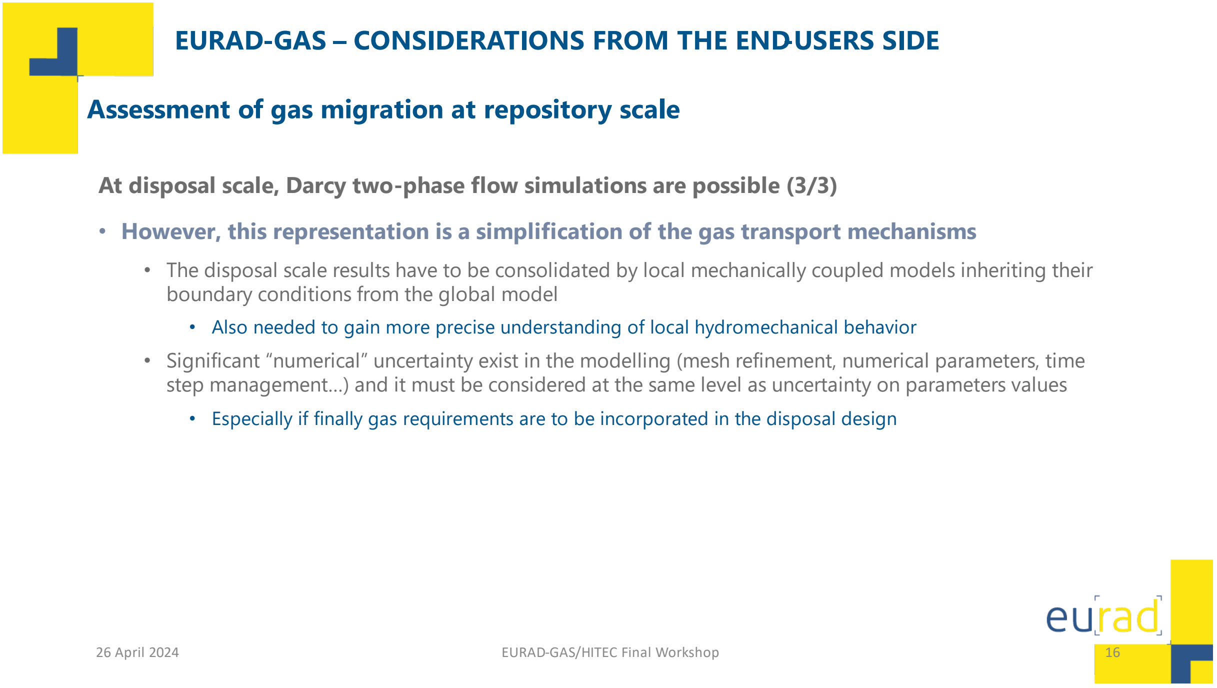


EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Assessment of gas migration at repository scale

At disposal scale, Darcy two-phase flow simulations are possible (2/3)

- **This representation is considered representative of the main phenomena developing during the hydraulic-gas transient provided that the estimated pressures remain lower than the gas fracturing pressure.**
  - This is partly due to the fact that Darcy type representation generalized to two-phase flow includes, via the Specific Storage, a simplified representation of an elastic type mechanical coupling assuming constant porosity (compressibility coefficient)
    - Particular attention must be paid to the value of this coefficient which must be equal to the inverse of the Biot modulus (i.e. "mechanical name" of the specific storage)
  - A good measurement of the mechanical behavior of the materials is then necessary to confirm that the estimated pressures remain in the linear (elastic) part of this behavior (i.e. belowgaz fracturing pressure)
- **This representation is also conservative in terms of gas pressure estimation compared to a mechanically coupled model**
  - Mechanical damage implies permeability increase (i.e. pressure dropdown) not taken into account in Darcy formulation



EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Assessment of gas migration at repository scale

At disposal scale, Darcy two-phase flow simulations are possible (3/3)

- **However, this representation is a simplification of the gas transport mechanisms**
  - The disposal scale results have to be consolidated by local mechanically coupled models inheriting their boundary conditions from the global model
    - Also needed to gain more precise understanding of local hydromechanical behavior
  - Significant "numerical" uncertainty exist in the modelling (mesh refinement, numerical parameters, time step management…) and it must be considered at the same level as uncertainty on parameters values
    - Especially if finally gas requirements are to be incorporated in the disposal design

EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Assessment of gas migration at repository scale

In order to cope with to high estimated gas pressures, mitigation measures are possible

- **Try to reduce as much as possible the amount of metal present in the disposal after closure**
  - Remove before closure all the metallic part that are not necessary after closure
    - Railways
    - Cable support
  - Reduce the amount of metal in the concrete liner reinforcement
- **Design disposal closure system to accommodate gas transport**
  - Add non clay material (sand) to backfill and/or seals

If possible, add management of gas requirements together with all other requirements early in the design stage

EURAD-GAS – CONSIDERATIONS FROM THE END-USERS SIDE

Assessment of gas migration at repository scale

Under Darcy two-phase flow assumptions, simulations of gaseous and soluble radionuclides transfer are possible at disposal scale

- **The transfer of gaseous radionuclides is very significantly increased compared to a hypothesis of hydraulic equilibrium (therefore water saturated) often used during long-term safety assessments.**
  - However, due to the relatively long transfer time from deposition cells/tunnels toward the shafts/ramps only radionuclides with sufficiently long ½ lives are arriving with significant fluxes under gaseous form in the upper aquifer (quantification is concept dependent)
  - *Not relevant for all national programs*
- **The transfer of soluble radionuclides via the gallery network to the surface-bottom connections may be delayed, compared to a hypothesis of hydraulic equilibrium upon closure of the repository, due to a hydraulic-gas transient involving partial desaturation of the EBS during typically several tens of thousands of years (quantification is concept dependent)**

Appendix A. List of participants

Name	First name	Organization	Type of organization	Country	
Bernier	Frédéric	FANC	TSO	BE	on-site
Bésuelle	Pierre	CNRS-3SR, Grenoble	RE	FR	online
Bird	Elliot	BGS	RE	UK	on-site
Cernochova	Katerina	CTU in Prague	RE	CZ	on-site
de Lesquen	Christophe	Andra	WMO	FR	on-site
Dizier	Arnaud	EURIDICE	RE	BE	online
Dymitrowska	Magdalena	IRSN	TSO	FR	on-site
Fletcher	Cameron	BGS	RE	UK	on-site
Gens	Antonio	UPC	RE	SP	online
Gimeno	Natalia	CIEMAT	RE	SP	on-site
Georgieva	Temenuga	EURIDICE	RE	BE	online
Gonzalez-Blanco	Laura	CIMNE	RE	SP	on-site
Graham	Caroline	BGS	RE	UK	on-site
Granet	Sylvie	EDF	RE	FR	on-site
Graupner	Bastian	ENSI	TSO	CH	on-site
Grgic	Dragan	CNRS - U. Lorraine	RE	FR	on-site
Gurau	Daniela	IFIN-HH	RE	RO	on-site
Harrington	Jon	BGS	RE	UK	on-site
Hausmannová	Lucie	SÚRAO	WMO	CZ	on-site
Hesketh	James	Jacobs	RE	UK	on-site
Jacops	Elke	SCK CEN	RE	BE	on-site
Kašpar	Vlastislav	ÚJV Řež	RE	CZ	on-site
Kirby	Matthew	NWS	WMO	UK	on-site
Kucerova	Marketa	CTU in Prague	RE	CZ	online
Leon-Vargas	Paola	BGE	WMO	DE	online
Leupin	Olivier X	Nagra	WMO	CH	on-site
Levasseur	Séverine	ONDRAF/NIRAS	WMO	BE	on-site
Llabjani	Qazim	EPFL	RE	CH	on-site
Maes	Norbert	SCK CEN	RE	BE	on-site
Marshall	Paul	Nagra	WMO	CH	on-site
Martin	Pedro Luis	CIEMAT	RE	SP	online
Mayor	Juan Carlos	Enresa	WMO	SP	on-site

Name	First name	Organization	Type of organization	Country	
Mayor Zurdo	Juan Carlos	ENRESA	WMO	SP	online
Mecová	Miroslava	SÚRAO	WMO	CZ	on-site
Mokni	Nadia	IRSN	TSO	FR	on-site
Narkuniene	Asta	LEI	RE	LT	on-site
Neeft	Erika	COVRA	WMO	NL	on-site
Niskanen	Mika	Posiva Oy	WMO	FI	on-site
Olin	Markus	VTT	RE	FI	on-site
Olivella	Sebastia	UPC	RE	SP	on-site
Papafotiou	Alexandros	Nagra	WMO	CH	online
Pirot	Véronique	Scriptio		BE	on-site
Pitz	Michael	BGR	RE	DE	on-site
Reddy	Bharti	NWS	WMO	UK	on-site
Saadi	Zakaria	IRSN	TSO	FR	on-site
Sentis	Manuel	ENSI	TSO	CH	on-site
Simo	Eric	BGE	WMO	DE	on-site
Smutek	Jan	SÚRAO	WMO	CZ	on-site
Song	Fei	UPC	RE	SP	online
Souley	Mountaka	Ineris	RE	FR	on-site
Svoboda	Jiří	CTU in Prague	RE	CZ	on-site
Syed	Naeem Ul Hasan	DSA	WMO	NO	on-site
Tatomir	Alexandru	BGE	WMO	DE	on-site
van Baelen	Hervé	ONDRAF/NIRAS	WMO	BE	online
Vašíček	Radek	CTU in Prague	RE	CZ	on-site
Večerník	Petr	ÚJV Řež	RE	CZ	on-site
Villar	María Victoria	CIEMAT	RE	SP	on-site
Weetjens	Eef	SCK CEN	RE	BE	online
Wendling	Jacques	Andra	WMO	FR	on-site
Ziefle	Gesa	BGR	RE	DE	on-site
Zuidema	Piet	Nagra	WMO	CH	on-site

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