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EURAD GAS AND HITEC: MECHANISTIC UNDERSTANDING OF GAS AND HEAT TRANSPORT IN CLAY-BASED MATERIALS FOR GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE

S. LEVASSEUR, X. SILLEN, P. MARSCHALL, J. WENDLING, M. OLIN, D. GRGIC, J. SVOBODA

CONCEPTUALIZATION OF GAS AND HEAT TRANSPORT TROUGH REPOSITORY IN CLAYEY HOST FORMATIONS AS CONSIDERED IN EUROPE

Contributions and key challenges of the EURAD RD&D WPs GAS and HITEC

GAS: *Mechanistic understanding of gas transport in clayey materials*

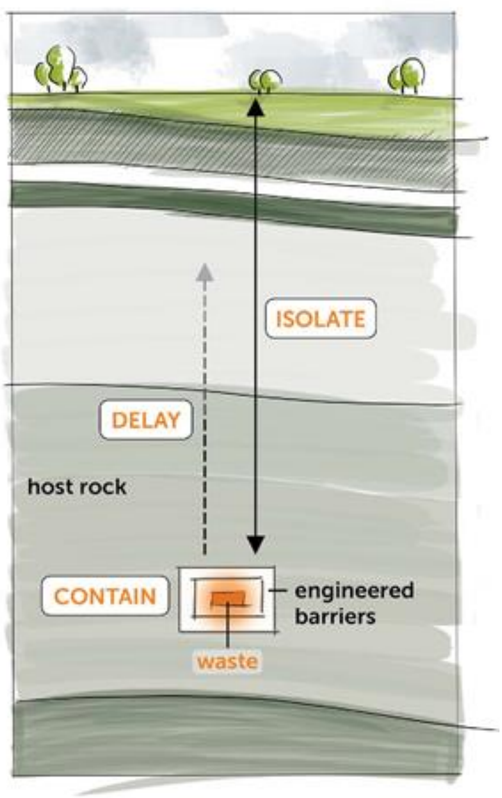
HITEC: *Influence of Temperature on Clay-based Material Behaviour*

Geological disposal of radioactive waste

The disposal system consists of the waste, the engineered barriers and the host rock → **Multi-barrier system to contain and isolate the waste from the biosphere**

- Each of these elements need to fulfil, separately or in complementary fashion, multiple safety functions
  - Natural barrier (host rock) has to provide stable environment allowing the engineering barrier system (EBS) to function from hundreds to many thousands of years
  - Geological barrier itself has to contribute to the confinement of radionuclides that would eventually be released after degradation of the engineered barriers

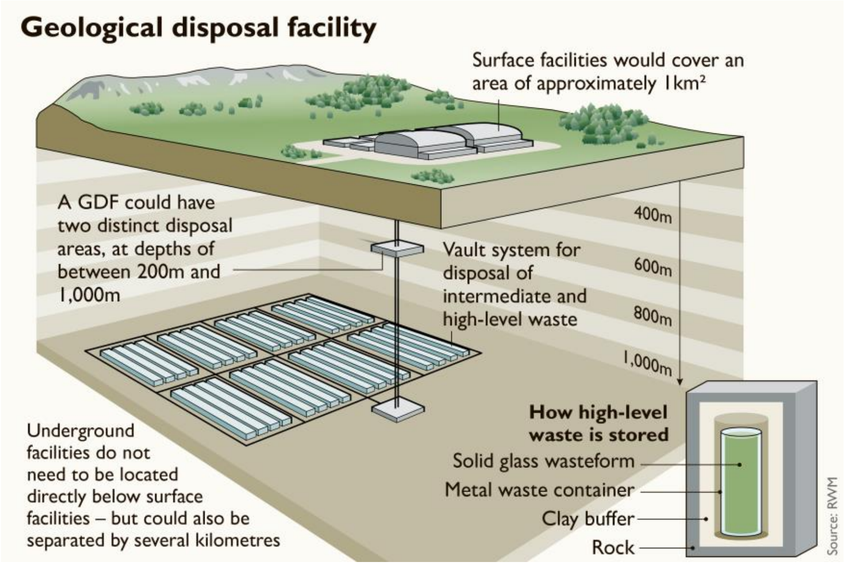
→ The 'defense-in-depth' principle requires multiple levels of protection, which are designed to enhance safety through their diversity and redundancy



Clay-based materials for geological disposal of radioactive waste

Clays exhibit excellent properties for the radionuclide containment and confinement which are exploited in the development of most geological disposal systems in Europe

→ *used both as host rock and as material for engineered barriers*



Geological disposal facility concept by RWM

Clay as host rock

- The research and development studies performed in France, Switzerland and Belgium over several decades have highlighted the clays' favorable properties:

Very little water movement thanks to their low permeability → radionuclide and chemical contaminant transport via this medium is thus strongly delayed

Diffusive transport given the limited water movement → species migrate primarily under the influence of their concentration gradient, and very little under the influence of the pore-water movement

Strong retention capacity for many radionuclides and chemical contaminants → their migration through clays is thus considerably delayed

Self-sealing capacity: any fractures and fissures that occur, in particular those created by excavation activities, close quite rapidly

Buffer effect with regard to chemical perturbations → the thickness of the clay that is chemically perturbed by the disposal facility is therefore very limited

Vertical homogeneity of radionuclide and chemical contaminant transport properties throughout the entire thickness of the selected clay host rocks

Lateral continuity: simple geological structures which facilitates their large-scale characterization

Hydrogeologically, geochemically and mechanically **stable** over geological timescales, i.e., millions of years

Clay as material for engineered barriers

- The favorable properties of clay (low permeability, self-sealing, retention capacity) make it a material of choice for engineered barriers. Clay is mainly used as:

Buffer material: the empty space between the disposal package and the host rock is filled with clay. E.g., bentonite, a swelling clay, is used as buffer material filling the voidage between the disposal packages and the host rock in the disposal facility designs selected in Canada, Finland, Sweden and Switzerland

Backfill material: clay (for instance in the form of blocks or pellets) is used to fill excavated spaces (placement rooms, access ways), sometimes in combination with other materials

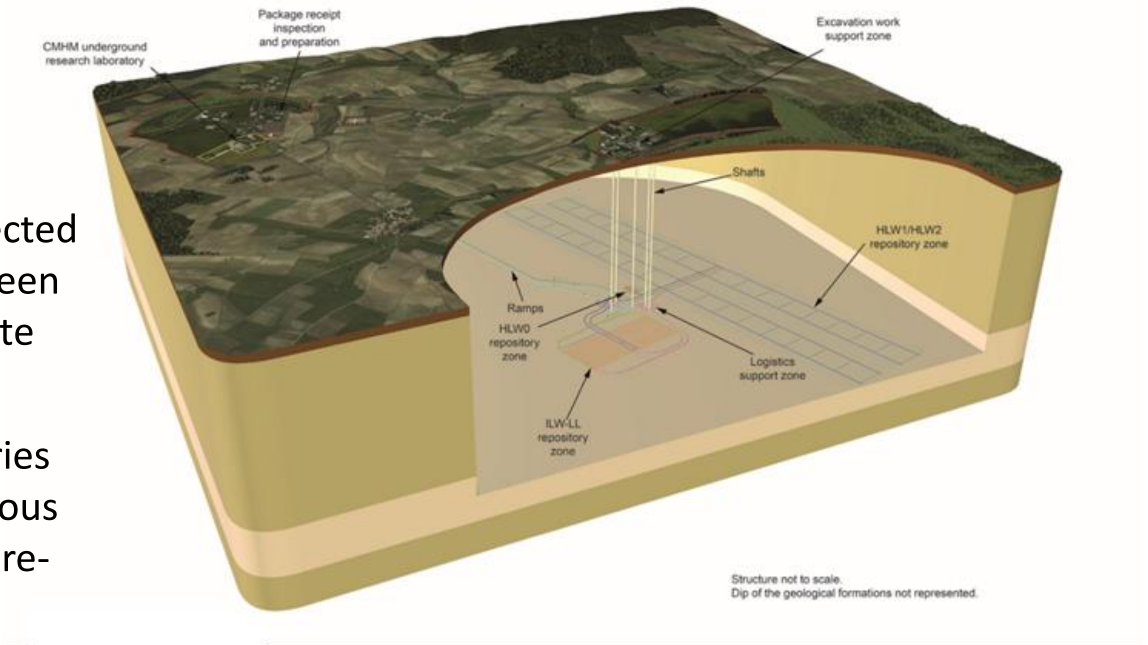
Sealing material: clay, sometimes in combination with other materials, is used to isolate parts of the disposal facility. Seals are works of limited dimensions with specific purpose placed at key locations of the disposal facility. E.g., the seals aim to limit water flow within the underground facilities

Deep geological repositories for the disposal of radioactive waste

Repository design approaches in clayey host formations as considered in Europe

For the moment, only France has selected a site in a clayey host rock, so it has been possible for Andra to define a complete repository concept for that site.

National programmes of other countries considering clay host rocks are at various stages of searching for a site and/or pre-design of a more generic repository concept.



Global architecture of the French repository (Cigéo)

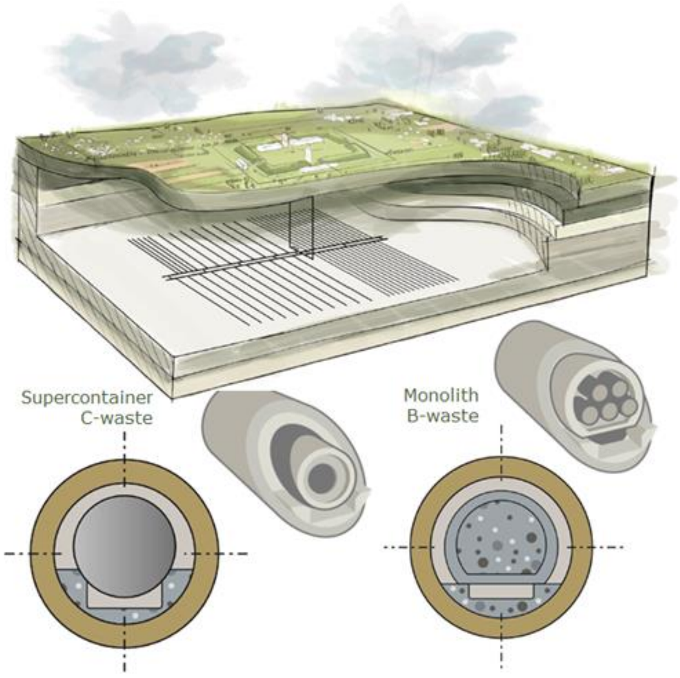
Deep geological repositories for the disposal of radioactive waste

All countries considering clay host rocks are:

– targeting clay layers at a **depth of a few hundred metres** in their search for a site
– planning a **single level disposal with separate zones** for high-level waste (HLW) disposal and long-lived intermediate-level waste disposal (LL-ILW)

Concepts are different depending of:

– the geometry of the primary waste packages,
– the volumes of waste to be disposed of
– the need to delay the migration of radionuclides as long as possible for each type of wastes.
– the management of the thermal phase for heat emitting waste & of the gas produced by the waste, its packaging and/or the EBS



Artistic view of a geological disposal facility (ONDRAF/NIRAS 2020)

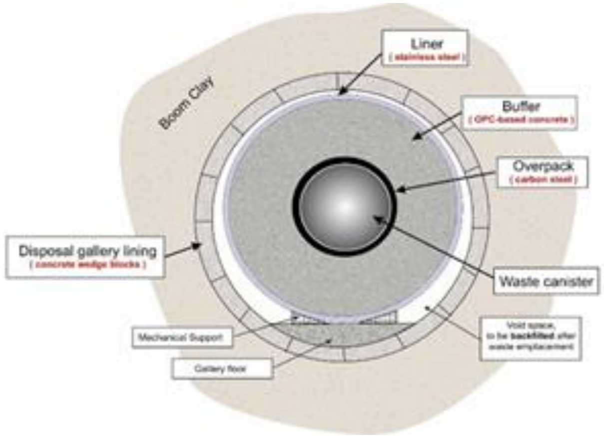
Repository design and thermal phase

To guarantee that the migration of radionuclides will be delayed as long as possible for heat emitting waste → no alteration of the clay properties has to be induced by high temperatures

Geometry of the primary waste packages (Example of HLW and Spent Fuel):

In all concepts:

- a metallic component (*Overpack*) to ensure the containment function:
  - at least while the thermal phase lasts
  - will degrade by corrosion (generates gas)
- *buffer* material (concrete in Belgium, bentonite in Switzerland or grout in France) to limit corrosion rate



Supercontainer design for HLW (ONDRAF/NIRAS 2013)

Heat source geometry is almost linear and relatively long

→ *gallery spacing adapted to limit T and its impact on the EBS, the near & far filed host rock*

Repository design and thermal phase

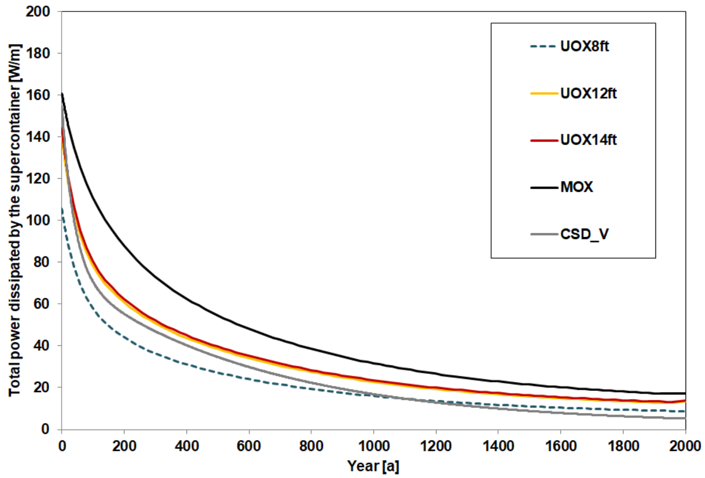
Radioactive decay of waste produces heat:

Heat output decreases rapidly in time, more so for HLW than for SF.

Heat produced is transported mainly by thermal conduction to the bedrock surrounding the repository

Criticality and thermal criteria have to be taken into account in design:

→ **no damage of the clay host formation should be caused by thermal loading**

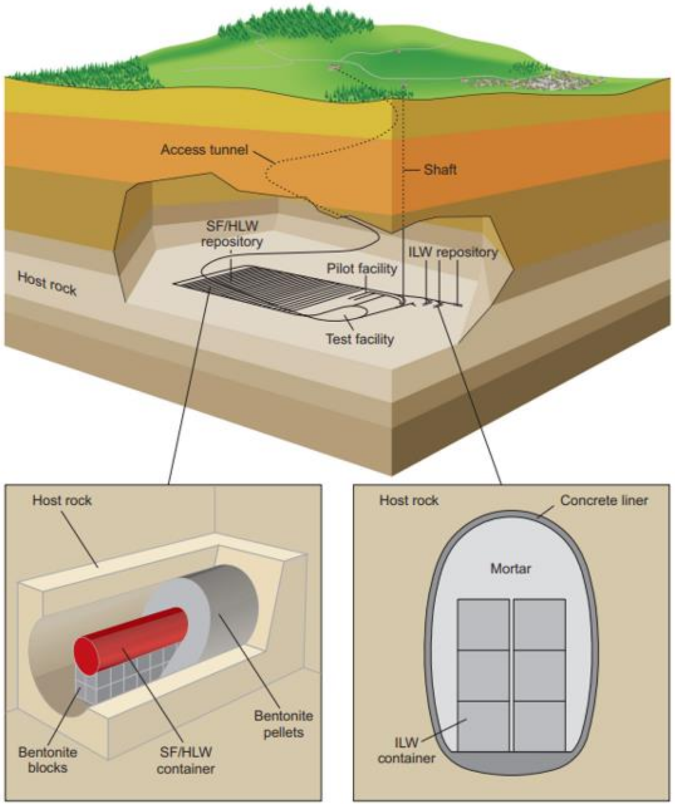


Heat fluxes at the gallery wall (time zero corresponds to the beginning of the thermal phase) (EURIDICE, 2020)

Repository design and thermal phase

→ **Most concepts limit maximum disposal container surface temperatures to 100°C to protect clay-based buffer, backfill and host rock materials from undesirable evolution**

- Management of the thermal phase for HLW
  - HLW disposal cells are generally smaller in diameter than LL-ILW disposal cells
  - waste disposal packages are disposed horizontally with only one package per cell section
- Heating large volume of the rock by conduction takes time
  - T constraints in the near field determine spacing between disposal packages
  - T constraint in the far field: determine spacing between galleries



Schematic layout of the Swiss repository (Nagra 2016)

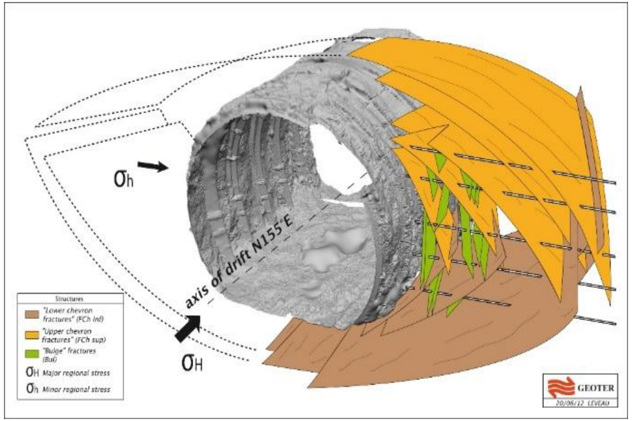
Repository design and thermal phase

- **Thermal perturbations studied since long time for clay-based materials exposed to temperatures lower than 100°C**
  - Thermo-Hydro-Mechanical behaviour of clayey materials is well-known
  - Upscaling from lab scale to repository scale has been demonstrated
  - Under these conditions,
    - ☺ clay-based buffer, backfill and host rock materials are protected from undesirable evolution
    - ☹ But, very long surface cooling times, many disposal containers and transport operations, large footprint of the facilities.

- **In the perspective of optimizing repository design, need to investigate THM behaviour of clay-based materials exposed to higher temperature (>100°C)**
  - *Are clayey-based materials able to tolerate temperature higher than 100°C and still ensuring an appropriate performance?*

Questions to be addressed

- **In clay host formations** (low permeable media)
  - When temperature increases, the pore water is pressurized because of the difference between its thermal expansion coefficient and that of the solid skeleton of the clay
    - In the near field characterized by an excavation damaged zone (EDZ), this could induce fracture re-opening or propagation, thus increasing the permeability.
    - In the far field, this could induce damage and reactivate fractures/faults (thermal frac).
  - **Need to evaluate damage evolution during the temperature transient phase and assess their consequences**



Conceptual model of the excavation induced fractures network in Callovo-Oxfordian claystone

- **In buffer bentonite**
  - When temperature increases, it may result in changes of buffer material, strong evaporation near the heater and vapor movement towards the external part of the buffer
  - **Need to evaluate the temperature impact on temperature dependent processes either after a high temperature exposure or while the clay is at the high temperature** (e.g., swelling capacity of bentonite)

EURAD-HITEC objectives

EURAD-HITEC: *“Influence of temperature on clay-based material behaviour”*

- **Topic:** consequences of the heat produced by the waste on the properties and long-term performance of the natural and engineered clay barrier
- **Objectives:**
  - **develop improved thermo-hydro-mechanical (THM) understanding of clay-based materials exposed at high temperatures** (>100°C) or having experienced high temperature transients for extended durations.
  - **evaluate whether or not elevated temperature limits are feasible for a variety of geological disposal concepts for high heat generating wastes (HLW)**

Deploy new knowledge to mechanics of host clay formations and clayey buffer at high temperature in support of the optimization of the design architecture of the deep geological disposal

Deep geological repositories for the disposal of radioactive waste

Generation of post-closure gases for each type of wastes

- Mostly hydrogen, produced by anaerobic corrosion of steel and reactive metals present in the waste, in their packaging and in the EBS
  - High-level waste overpacks made of steel → important source of hydrogen
  - Metallic elements of gallery lining (reinforcing bolts, and/or concrete reinforcement)
  - Some long-lived intermediate-level waste contains (mainly or partially) metallic elements
- Degradation of organics wastes & radiolysis also produce gas

→ **Significant volumes: several times the excavated volume (under standard pressure and temperature conditions) but generated over a long time period (corrosion rates are generally expected to be very low), can be pressurized (up to a certain point) and can be evacuated in different ways**

Repository design and production/evacuation of gases

To guarantee that the migration of radionuclides will be delayed as long as possible for each type of waste → no alteration of the clay properties has to be induced by gas production and evacuation

Generation of post-closure gases for each type of wastes

Most concepts adapt the general architecture of the repository to have

- → **Sufficient expansion volume available in the porosity of the EBS, buffer & backfill** for the gases generated after closure
  - E.g., role of the seals in this context: limit gas overpressure by letting it through within a certain pressure range and still remain tight for water.
- → **Continuous release and evacuation through dissolution and diffusion or along existing pathways through the EBS, EDZ or interfaces by visco-capillary two-phase flow**

Repository design and production/evacuation of gases

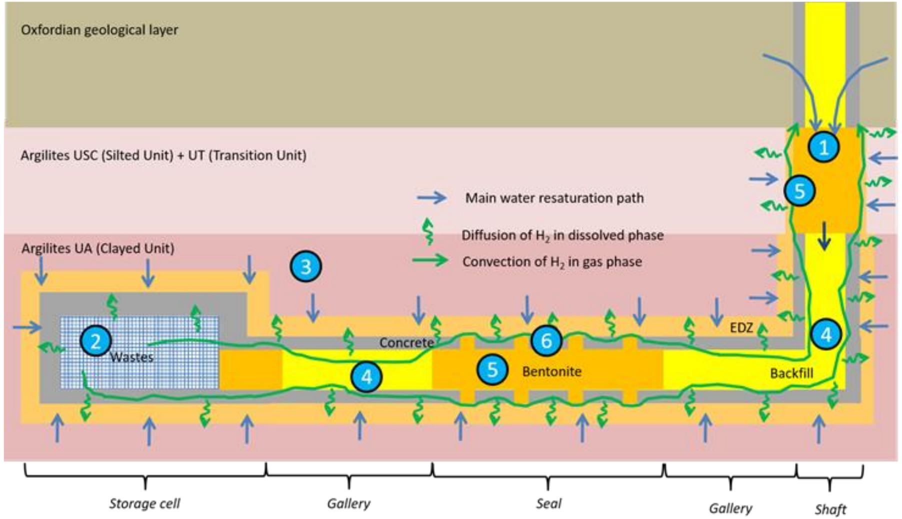
- **Even though the gas production processes are generally slow, how to ensure that these will not be detrimental to the good functioning of the disposal system?**

  – Gas is first evacuated by diffusion of dissolved gas

    – The low permeability of clays is favorable with respect to the containment function of a repository but limits the evacuation of the generated gas

  – If diffusion not sufficient, development of a pressurised gas phase within the repository and its surrounding

    – *Does the accumulated gas escape from the repository by discrete, gas-specific pathways through the EBS and/or the host rock that affect barrier integrity?*



Repository design and production/evacuation of gases

- **Impacts of gas perturbations less well controlled than thermal impacts**
  - **Gas transport by diffusion of dissolved gas:** well-known and can be upscaled
  - **Gas transport by visco-capillary two-phase flow:** well-known; controlled by the fabric of the material; observed indirectly, through its effects on permeability
  - **Gas transport through gas specific pathways:**
    - discrete, unstable pathways controlled by the mechanical behaviour of the porous media

    → *How and to what extent could the hydro-mechanical perturbations induced by gas affect barrier integrity and performance?*
    - Direct upscaling not feasible → *How can gas migrate within the repository and which water soluble and volatile radionuclide transport could be associated with that?*
  - **Need to transfer knowledge gained from laboratory and in situ experiments to configurations that are commonly found in current repository designs in clays**
    - Provide results that are applicable to a wide range of national programmes

EURAD-GAS objectives

EURAD-GAS: *"Mechanistic understanding of gas transport in clayey materials"*

- **Topic:** gas transport in natural and engineered clayey materials
- **Objectives:**
  - **improve the mechanistic understanding of gas transport processes in clayey materials**, their couplings with the mechanical behaviour and their impact on the properties of these materials;
  - **evaluate the gas transport regimes that can be active at the scale of a geological disposal system** in clayey host formations and their potential impact on clayey barrier integrity and repository performance

Increase confidence in the understanding gained from FORGE EC project,

Improving its integration in the conceptualisation process for the different clayey components of a disposal system,

Support and justify the use of robust evaluation approaches,

Confirm the expert judgment at the end of FORGE that gas is not a showstopper for geological disposal but a question of managing uncertainties.

Common challenges of EURAD-GAS & EURAD-HITEC

- These two WPs strongly builds on the results, return of experience and conclusions from past EC projects (e.g., TIMODAZ, FORGE, BEACON) which revealed complex mechanisms but also hinted that these could probably be addressed using a combination of simple and robust approaches

- **The main challenges of EURAD-GAS and EURAD-HITEC lies in the stepwise integration and contextualization of experimental results and modelling approaches**
  - Increase the understanding and predictability of the impact on clay barriers, from the study of fundamental mechanisms and their couplings related to gas and heat transport, observed at lab scale or via past and present in-situ experiments
  - Build models of different complexity to support the understanding of the observed mechanisms and transfer it to the configurations and conditions of the different clayey components and the context of the functioning of a disposal system
  - Transparent about the context in which any piece of data has been collected or any model has been developed, key uncertainties but also to clearly communicate all elements of scientific consensus

Common challenges of EURAD-GAS & EURAD-HITEC

By providing the end-users with a collection of data, tools and building blocks for storyboards that may be of use in the conceptualization of the functioning of their specific geological disposal system, the WPs GAS and HITEC of the European Joint Programme EURAD will contribute to the development of simple and robust (but phenomenologically-based) approaches and support the justification of their use

Thank you for your attention

European Joint Programme on Radioactive Waste Management

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