Journal of Rock Mechanics and Geotechnical Engineering 5 (2013) 277–286

Journal of Rock Mechanics and GeotechnicalEngineering

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

# Simulations of THM processes in buffer-rock barriers of high-level waste disposal in an argillaceous formation

Xiaoshuo Li[a,*], Chunliang Zhang[b], Klaus-Jürgen Röhlig[a]

[a] Institute of Disposal Research, Clausthal University of Technology, Clausthal-Zellerfeld 38678, Germany
[b] Gesellschaft für Anlagen- und Reaktorsicherheit mbH, Braunschweig 38118, Germany

A R T I C L E I N F O

*Article history:*
Received 4 April 2012
Received in revised form 6 June 2012
Accepted 3 September 2012

*Keywords:*
Thermo-hydro-mechanical (THM) coupling processes
Clay formation
Unsaturated porous media
Bentonite buffer
CODE_BRIGHT

A B S T R A C T

The main objective of this paper is to investigate and analyse the thermo-hydro-mechanical (THM) coupling phenomena and their influences on the repository safety. In this paper, the high-level waste (HLW) disposal concept in drifts in clay formation with backfilled bentonite buffer is represented numerically using the CODE_BRIGHT developed by the Technical University of Catalonia in Barcelona. The parameters of clay and bentonite used in the simulation are determined by laboratory and in situ experiments. The calculation results are presented to show the hydro-mechanical (HM) processes during the operation phase and the THM processes in the after-closure phase. According to the simulation results, the most probable critical processes for the disposal project have been represented and analyzed. The work also provides an input for additional development regarding the design, assessment and validation of the HLW disposal concept.



## 1. Introduction

Radioactive waste is a consequence of using radioactive materials in industrial, medical, military and research applications. For high-level waste (HLW), spent fuel (SF) and all long-lived waste categories, geological disposal at depths of some hundreds of metres is considered worldwide as the most safe and feasible method to protect human beings and the environment for extremely long periods of time (IAEA, 1993).

Clay formations are being widely investigated as host media for deep disposal of radioactive waste, such as the plastic Boom Clay in Belgium, the highly indurated Opalinus Clay in Switzerland and the Callovo-Oxfordian argillite in France. They are characterized by very low permeabilities of $10^{-19}$–$10^{-21}$ m$^2$. The porosity varies from 0.14 to 0.37. Clays offer high sorption capability for most radionuclides. The plasticity and self-sealing/healing properties of most clay rocks also contribute to the restoration of pre-existing and excavation-induced cracks. All of these properties provide great advantages for reliable long-term confinement and isolation of radioactive waste from the biosphere. The disposal concepts rely on a multi-barrier system with natural geological barriers provided by the repository host rock and its surroundings and the engineered barriers within the repository. The capability of natural barriers for long-term isolation of radionuclides from the environment and their long-term stabilities are the key reasons for the geological disposal of radioactive waste. The engineered barrier system represents the man-made, engineered materials placed within a repository, including waste form, waste containers, buffer materials, backfill, and seals (OECD, 2003).

The French repository designed by French ANDRA in 2005 is located in the middle of the Callovo-Oxfordian argillaceous formation (COX) of 250 m thickness at a depth of 500 – 630 m below the ground surface. In order to maximize the length of the radionuclide transport to adjacent formations both above and below the repository, horizontal disposal in drifts, rather than vertical disposal in boreholes, is selected. The HLW containers with 430 mm in diameter and 1335 mm in length will be emplaced in dead-end boreholes (700 mm in diameter, 40 m long) with liner, as shown in Fig. 1. These cells are spaced approximately 10 m apart and each one receives 6–8 containers. The remaining space between HLW containers and cell walls will be backfilled with compacted bentonite-based buffer materials. Due to the excavation, ventilation, backfilling operation and the heat power of the emplaced HLW, the primary thermo-hydro-mechanical (THM) state of the clay formation with high water content will be disturbed. Thus,

* Corresponding author. Tel.: +49 05323 724923.
*E-mail address:* xiaoshuo.li@tu-clausthal.de (X. Li).

Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

Production and hosting by Elsevier

1674-7755 © 2013 Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. Production and hosting by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jrmge.2012.09.002

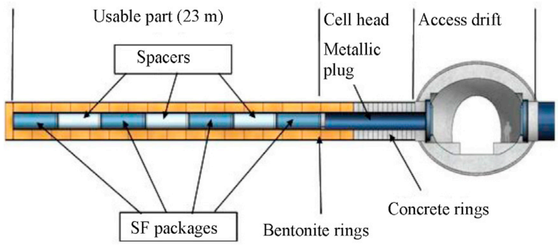


**Fig. 1.** French concept for disposal of HLW in horizontal borehole (ANDRA, 2005a).

long-term THM processes should take place, which may have influence on the confinement capability of the disposal concept against the release of emplaced radioactive materials. For this reason, a study of the long-term THM phenomena during and after the repository operation is necessary for the long-term safety assessment of the disposal concept.

Although bentonite buffer will probably not be used between container and drift wall in the most current French disposal concept, it is interesting to obtain the THM processes in the two media. The main objective of this paper is to investigate and analyse the THM coupling phenomena in the rock-buffer system surrounding heat-emitting radioactive waste. The results will support the performance and safety assessment of repositories in clay formations.

## 2. Basic theories of THM modelling

### *2.1. THM coupling phenomena*

Geological and geotechnical materials, like rocks and backfill/buffer materials, are porous media. Generally, the porous media are composed of three species: mineral, water and air, distributing in three phases: solid, liquid and gas (Fig. 2). The liquid phase contains liquid water and dissolved air, while the gas phase is a mixture of dry air and water vapour.

In porous media subjected to hydraulic and mechanical conditions, complex THM phenomena and interactions take place. The THM processes of the porous media are coupled through some parameters. For instance, the heat transport (thermal) causes changes of the pore pressure and the fluid viscosity, which have influence on the water and gas flow (hydraulic). As shown in Fig. 3, the parameters, such as thermal conductivity and effective stresses, are considered as the bridge parameters for the coupling of the THM phenomena.

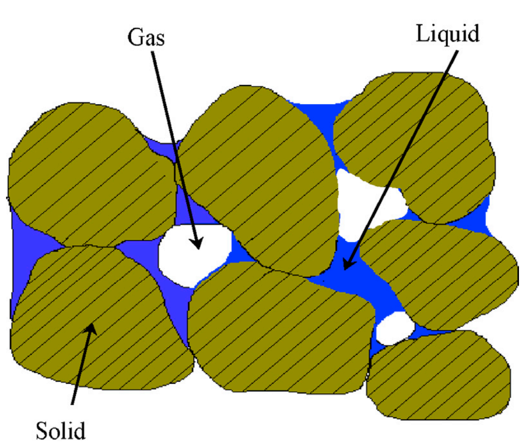


**Fig. 2.** Schematic representation of an unsaturated porous material (CODE_BRIGHT, 2004).

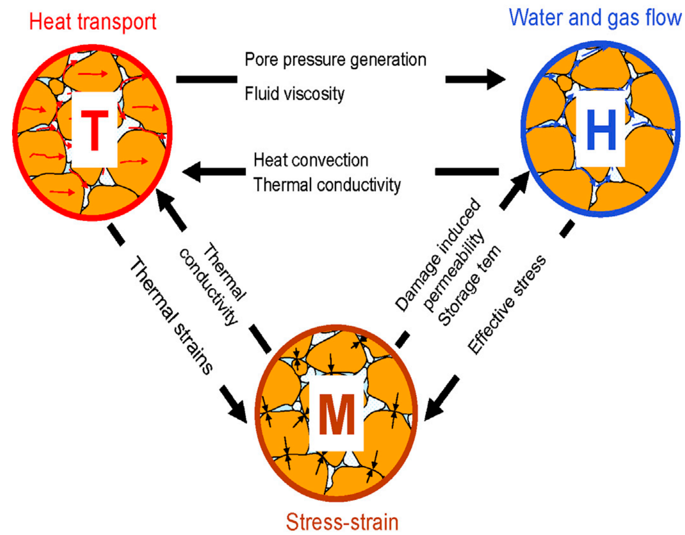


**Fig. 3.** Mutual relationships between THM processes in a porous medium (CODE_BRIGHT, 2004).

The aforementioned THM phenomena have been implemented in the CODE_BRIGHT. Details about the basic theories with the formulated governing equations are described in the code manual (CODE_BRIGHT, 2004) as well as other references (Olivella et al., 1994; Gens et al., 1998, 2007; OECD, 2003). In the following context, the balance equations and constitutive models, which are to be solved in the calculations, are briefly summarized. Values of the associated parameters for the Callovo-Oxfordian argillite and the FEBX compacted bentonite are taken from Gens et al. (1998, 2007), OECD (2003), Vaunat et al. (2003), Zhang et al. (2004), and Zhang (2009).

### *2.2. Balance equations*

Generally, for the calculations of coupled THM processes in geological media, a set of balance equations for internal energy, solid mass, water mass, air mass, and stress equilibrium are to be solved in a consistent way.

#### *2.2.1. Internal energy balance*

The internal energy balance can be written as:

$$\frac{\partial}{\partial t}[E_s\rho_s(1-\phi)+E_l\rho_l S_l\phi+E_g\rho_g S_g\phi]+\nabla\cdot(\boldsymbol{i}_c+\boldsymbol{j}_{Es}+\boldsymbol{j}_{El}+\boldsymbol{j}_{Eg})=f^E \tag{1}$$

where $E_s$, $E_l$ and $E_g$ are specific internal energies corresponding to the solid, liquid and gas phases (J/kg), respectively; $\rho_s$, $\rho_l$ and $\rho_g$ are the densities of the three phases (kg/m$^3$); $\phi$ is the porosity of the total media; $S_l$ is the volumetric liquid fraction (%) and $S_g$ is the volumetric gas fraction with respect to the pore volume (%), $S_l+S_g=1$; $f^E$ is the energy supply per unit volume of the considered media (J/s); $\boldsymbol{i}_c$ is the conductive heat flux; and $\boldsymbol{j}_{Es}$, $\boldsymbol{j}_{El}$, $\boldsymbol{j}_{Eg}$ are the advective energy flux of each of the three phases with respect to a fixed reference system (J/s). The most relevant advection energy fluxes correspond to vapour and liquid water motion.

#### *2.2.2. Water mass balance*

The water mass balance can be written as:

$$\frac{\partial}{\partial t}(\theta_l^w S_l\phi+\theta_g^w S_g\phi)+\nabla\cdot(\boldsymbol{j}_l^w+\boldsymbol{j}_g^w)=f^w \tag{2}$$