KSCE Journal of Civil Engineering (2011) 15(4):721-737
DOI 10.1007/s12205-011-0012-8

Energy Geotechnology
www.springer.com/12205

Geological Storage of High Level Nuclear Waste

Jin-Seop Kim*, Sang-Ki Kwon, Marcelo Sanchez***, and Gye-Chun Cho******

Received August 31, 2010/Accepted February 16, 2011

Abstract

The quantity of radioactive waste will grow significantly with an increasing interest and use of nuclear-generated energy. There will always be inevitable radioactive waste residues that require disposal, even using an advanced nuclear fuel cycle in the future. Deep geological disposal, one of the most promising final disposal methods, should be validated for its long-term performance and safety assessment. Geotechnical issues related to the deep geological disposal are critical for the sustainable development of nuclear energy. They play challenging roles especially under extreme circumstances that result from deep geological conditions of a repository, extremely long containment time, and the characteristics of nuclear waste itself such as high decay heat, which may primarily affect thermo-hydro-mechanical and geochemical-coupled behavior of a repository for geologic time scales. This paper introduces an overview of deep geological disposal concepts based on Finnish, Korean, Spanish, and Swedish disposal programs, discusses the outstanding research issues in disposal from the aspect of geological and geotechnical engineering, such as Excavation-Damaged Zone (EDZ), cementitious material, long-term gas migration, and self-sealing/healing of fractured rocks with a focus on the state of the art in-situ validation experiments, and additionally presents a numerical modeling of the coupled THMG process in the repository near field, which is one of the major factors concerning the fuel canisters.

Keywords: *coupled THMG modeling, deep geological disposal, excavation-damaged zone, gas migration, self-sealing/healing, spent nuclear fuel*

1. Introduction

In the midst of increased concern about carbon emissions and global warming, non-fossil fuel alternatives are gaining increased attention, in particular to nuclear power. The OECD Nuclear Energy Agency (NEA) (2008) declared that nuclear power could play a very powerful role in delivering cost-competitive and stable supplies of energy while also helping to reduce greenhouse gas emissions. With this trend, eleven nuclear power plants worldwide newly launched construction in 2009, which is the largest number since 1987; ten of the eleven plants are being constructed in Asia. A total of 437 reactors in 31 countries in the world are in operation now and 56 nuclear reactors are under construction (IAEA, 2010). It is anticipated that by 2050 the amount of nuclear-generated electricity worldwide will have increased a minimum of 1.6 times and a maximum of 3.9 times from its 2008 value of 372 GWe (OECD NEA, 2008). Taking into account that the identified uranium reserve (under 130 $/kg) is 5.7 million tons and uranium consumption in 2009 was estimated at 65,400 tons, it is expected that uranium will probably be in use for only ninety more years (IAEA, 2010).

With increased interest in nuclear-generated energy, radioactive waste will grow at the same time. There have been three main strategies for managing spent nuclear fuel: reprocessing, storage and direct disposal. Different countries place different degrees of emphasis on these alternatives. Although the choice between them is determined by whether a country regards the fuel as waste or as a resource, it is primarily influenced by political or economic reasons in most countries, especially in cases in which the country has a reprocessing facility. A few countries have embarked on programs to decrease the amount of waste they have to dispose of and are trying to recycle/reuse nuclear waste in order to conserve existing uranium resources. Countries such as France, Japan, Russia, China, and India stick to national waste policies of reprocessing spent fuel and try to reduce the produced volume of High Level Waste (HLW) by reprocessing. Most European nations, such as Sweden and Finland, have been placing priority on the direct disposal system. The U.S.A and

---

*Senior Researcher, Radioactive Waste Technology Development Division, Korea Atomic Energy Research Institute (KAERI), Daejeon 305-353, Korea (E-mail: kverity@kaeri.re.kr)

**Principal Researcher, Radioactive Waste Technology Development Division, Korea Atomic Energy Research Institute (KAERI), Daejeon 305-353, Korea (E-mail: kwonsk@kaeri.re.kr)

***Associate Professor, Zachry Dept. of Civil Engineering, Texas A&M University, College Station, US. 3136 TAMU, College Station, TX 77843-3136 (E-mail: msanchez@civil.tamu.edu)

****Member, Associate Professor, Dept. of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 305-701, Korea (Corresponding Author, E-mail: gyechun@kaist.edu)

Table 1. Nuclear Power Reactors (as of 1 January 2010) and Waste Management Policy for Spent Fuel (Modified from IAEA, 2010 and WNA, 2009)

Country	Reactors in operation		Reactors under construction		Nuclear Electricity supplied in 2008		Policy	Facilities and progress towards final repositories
	No. of units	Total MW (e)	No. of units	Total MW (e)	TW-h	% of total		
Belgium	7	5,863	-	-	43.4	53.8	Reprocessing	· Central waste storage at Dessel / · Underground laboratory established 1984 at Mol/ · Construction of repository to begin about 2035
Canada	18	12,577	-	-	88.3	14.8	Direct disposal	· Nuclear waste management organization set up 2002 / · Deep geological repository confirmed as policy, retrievable / · Repository site search from 2009, planned for use 2025
China	11	8,438	20	19,920	65.3	2.2	Reprocessing	· Central used fuel storage at LanZhou / · Repository site selection to be completed by 2020 / · Underground research laboratory from 2020, disposal from 2050
Finland	4	2,696	1	1,600	22.1	29.7	Direct disposal	· Program start 1983, two used fuel storages in operation / · Posiva Oy set up 1995 to implement deep geological disposal / · Underground research laboratory Onkalo under construction / · Repository planned from this, near Olkiluoto, open in 2020
France	59	63,260	1	1,600	419.8	76.2	Reprocessing	· Underground rock laboratories in clay and granite / · Parliamentary confirmation in 2006 of deep geological disposal, containers to be retrievable and policy "reversible" / · Bure clay deposit is likely repository site to be licensed 2015, operating 2025
Germany	17	20,470	-	-	140.9	28.8	Reprocessing but moving to direct disposal	· Repository planning started 1973 / · Used fuel storage at Ahaus and Gorleben salt dome · Geological repository may be operational at Gorleben after 2025 /
India	18	3,984	5	2,708	13.2	2.0	Reprocessing	· Research on deep geological disposal for HLW
Japan	54	46,823	1	1,325	241.3	24.9	Reprocessing	· Underground laboratory at Mizunami in granite since 1996 / · High-level waste storage facility at Rokkasho since 1995 / · High-level waste storage approved for Mutsu from 2010 / · NUMO set up 2000, site selection for deep geological repository under way to 2025, operation from 2035, retrievable
S. Korea	20	17,647	6	6,520	144.3	35.6	Direct disposal	· Waste program confirmed 1998 / · Central interim storage planned from 2016
Russia	31	21,743	9	6,894	152.1	16.9	Reprocessing	· Underground laboratory in granite or gneiss in Krasnoyarsk region from 2015, may evolve into repository / · Sites for final repository under investigation on Kola peninsula / · Various interim storage facilities in operation
Spain	8	7,450	-	-	56.5	18.3	Direct disposal	· ENRESA established 1984, its plan accepted 1999 / · Central interim storage probably at Trillo from 2010 / · Research on deep geological disposal, decision after 2010
Sweden	10	8,958	-	-	61.3	42.0	Direct disposal	· Central used fuel storage facility-CLAB-in operation since 1985 / · Underground research laboratory at Äspö for HLW repository / · Osthammar site selected for repository (volunteered location)
Switzer-land	5	3,238	-	-	26.3	39.2	Reprocessing	· Central interim storage for HLW at Zwilag since 2001 / · Central low&ILW storages operating since 1993 / · Underground research laboratory for high-level waste repository at Grimsel since 1983 / · Deep repository by 2020, containers to be retrievable
U.K.	19	10,097	-	-	48.2	13.5	Reprocessing	· Low-level waste repository in operation since 1959 / · HLW from reprocessing is vitrified and stored at Sellafield / · Repository location to be on basis of community agreement / · New NDA subsidiary to progress geological disposal
U.S.A.	104	100,683	1	1,165	806.7	19.7	Direct disposal but reconsidering	· DoE responsible for used fuel from 1998, $32 billion waste fund / · Considerable research and development on repository in welded tuffs at Yucca Mountain, Nevada / · 2002 decision that geological repository be at Yucca Mountain was countered politically in 2009

Germany prefer the flexible management of spent fuel for changeable national environments such as advanced fuel cycle, long-term/interim storage and final disposal. The current status of nuclear power reactors and national waste management policies for spent fuel are summarized in Table 1.

Whatever advanced technique is developed in the future for recycling and reuse of spent fuel, however, there will always be some inevitable residue that requires final disposal, as shown in

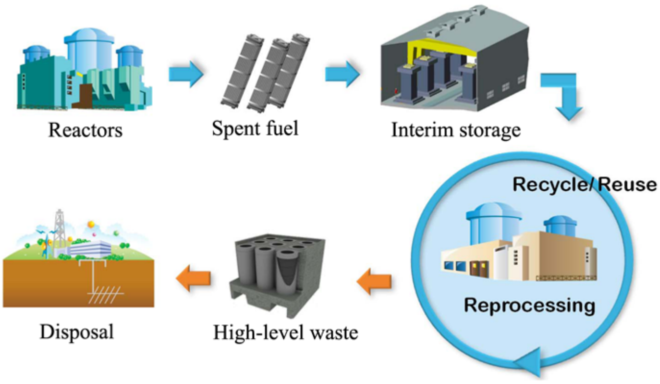


Fig. 1. The Back-end Fuel Cycle which Utilizes Advanced Management Techniques

Fig. 1. Although various radioactive waste disposal concepts, including deep-seabed disposal, disposal in the polar ice sheets, and rocketing waste into the space etc., have been investigated, deep geological disposal has been considered to be the most appropriate solution to deal with high level radioactive wastes and other long-lived radioactive wastes with respect to technical practicality, safety, cost and environmental impact (Bodansky, 1996; European Commission, 2004). Because of the increasingly stringent environmental regulation of radioactive hazardous waste and high demand for the wiser use of limited land surface, the choice of geological disposal of radioactive waste will be of more interest in the future. Since the first scientific research on geological disposal (NAS, 1957), there have been wide international cooperative studies (IAEA, 1993; NEA, 1999; IAEA, 2003a; IAEA, 2006; Alexander and McKinley, 2007). Although there is currently no final disposal repository in the world, Finland is close to being the first country that will have an operational spent fuel repository within the next ten years.

Compared to the conventional geo-engineering practices associated with the site investigation or construction/operation of an underground structure (e.g., excavation, stabilization, ventilation and drainage), radioactive waste geological disposal can be characterized by three salient features: (1) deep geological conditions of a repository, (2) extremely long containment time by using a series of natural and engineered barriers (e.g., even more than hundreds of thousands of years), and (3) characteristics of nuclear waste itself, such as emitting high decay heat and radioactivity. Such features provide challenging requirements for multidisciplinary collaboration among the fields of geotechnical, geological, and hydrogeological engineering (NA, 2006).

The thermal field around the repository will be significantly altered by the presence of canisters containing heat-emitting nuclear waste. In the near field of the repository, the distribution of water pressure will also be substantially affected by the construction of the gallery system, the desaturation induced by the waste canisters, and the presence of the (initially unsaturated) clay barrier (if any). Thus, it is expected that advective fluxes of water and gas will be driven by liquid and gas pressure gradients, mechanical changes will occur in the clay barrier and rock due to the heating, drying and wetting processes aforementioned, and solute diffusion and chemical reactions between the percolating fluid and the repository components will take place. These simultaneous actions will induce a number of Thermo-Hydro-Mechanical and Geochemical (THMG) processes that will significantly affect the evolution and long term performance of the isolation system.

This paper introduces an overview of deep geological disposal concepts based on Finnish, Swedish, and Spanish disposal programs, discusses the outstanding research issues in disposal from the aspect of geological and geotechnical engineering, such as Excavation-Damaged Zone (EDZ), cementitious material, long term gas migration, and self-sealing/healing of fractured rocks with a focus on state of the art in-situ validation experiments, and additionally presents a numerical modeling of coupled the THMG process in the repository near field, which is one of the major factors of concern regarding the fuel canisters.

2. Geological Disposal Concepts

The principle of geological disposal of radioactive waste (e.g., spent nuclear fuel, high-level waste, and long-lived radionuclides) is to place carefully prepared and packaged waste in excavated tunnels in geological formations such as salt, hard rock, or clay. The concept relies on a series of natural barriers and an Engineered Barrier System (EBS), called a multi-barrier, to contain the waste for a long time and to minimize the amount of radioactive material that may eventually escape from a repository and reach the human environment. The presence of multi-barrier systems serves a complementary safety function in that it increases confidence in the HLW repository. The potential design concept of the final repository for spent nuclear fuel and multi-barrier systems is shown in Fig. 2. Usually an EBS may be composed of a variety of sub-components, such as the waste form, the canisters, buffer materials, backfill, and plugs, to prevent and delay the release of radionuclides from the waste to the repository host rock. Detailed descriptions and explanations of the functions of the engineered barrier components are presented as follows.

2.1 Canisters

The canister in which the spent nuclear fuel will be encapsulated is the most important barrier for isolating the waste. The reference canister of Swedish Nuclear Fuel and Waste Management Company (SKB) is composed of an inner container of cast iron and an outer shell of copper, which are primarily used for its corrosion resistance. Researchers have mainly concentrated on canister fabrication/welding, deformation/corrosion behaviors and nondestructive testing (IAEA, 1997; IAEA, 2003b; Andersson *et al*., 2004). Corrosion derived from thermal stress and material modification of the cast iron insert from a high radiation dose, which has a tendency to make material more brittle, is currently under investigation. The behaviors of corrosion products at the

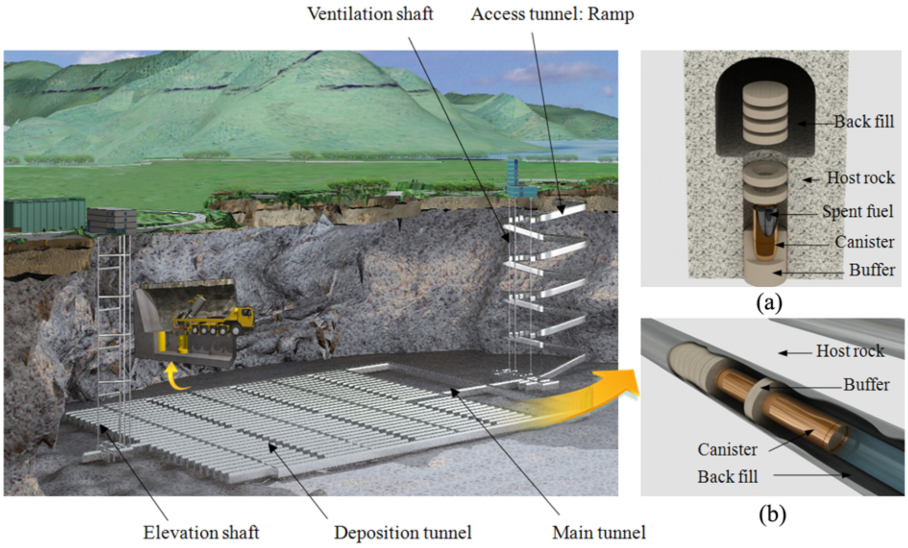


Fig. 2. Design Concept of the Final Repository for Spent Nuclear Fuel and Multi-barrier System: (a) Vertical Deposition, (b) Horizontal Deposition

interface between the steel canister and the backfill require further investigation.

2.2 Buffer

A buffer surrounding the canister is used to restrict the infiltration of groundwater around the canister and to provide the function of a colloid filter by rendering a diffusion barrier and a high sorption capacity against radionuclide migration (OECD-NEA, 2003). Japan Nuclear Cycle Development Institute (JNC, 2000) investigated some properties of the buffer, including the physical, thermal, hydraulic, and mechanical parameters, and specified its required design properties for both 100 wt.% bentonite and a bentonite (70%) - sand (30%) mixture. From studies both in the field and by numerical modeling, SKB (2007) has come up with performance indicators that the buffer must meet, as listed in Table 2.

Table 2. Performance Indicators for the Buffer (SKB, 2007)

Performance indicator	Criterion	Background
Hydraulic conductivity	$k^{Buffer} > 10^{-12}$ m/s	Limit mass transport to a diffusion-dominated process
Swelling pressure	$P_{swell} > 1$ MPa	Ensure sealing, self-healing capacity
Maximum temperature	$T^{Buffer} < 100^{o}$C	Ensure that the buffer retains its properties for long periods of time
Minimum temperature	$T^{Buffer} > -5^{o}$C	Prevent freezing
Swelling pressure against the canister	$P_{swell} > 0.2$ MPa	Prevent the canister from sinking
Swelling pressure around the canister	$P_{swell} > 2$ MPa	Prevent microbial activity
Density around the canister	$\rho_{Bulk} > 1{,}650$ kg/m^3	Prevent transport of particles through the buffer
Density around the canister	$\rho_{Bulk} < 2{,}100$ kg/m^3	Limit shear stresses on the canister due to rock movements

The elevated temperature from the decay heat of waste will change the mineralogical, geomechanical and hydraulic properties of bentonite clays. Thus, the surface temperature of waste packages should be maintained at less than 100°C to prevent water vapor production and a change in the suction potential of bentonite. When the bentonite buffer is emplaced, it will experience dehydration induced by the heat emitted from the waste and rehydration induced by the ground water ingression, which may change the suction potential of bentonite. Elevated temperature, groundwater and corrosion products from waste and the steel canister will also alter the mineralogical characteristics in the bentonite, possibly by changing the hydraulic properties due to precipitation or dissolution of minerals (Falck and Nilsson, 2009).

While the response of bentonite to changing conditions such as water content, thermal gradient, salinity/pH of ground water etc. are relatively well known, the combined effect and possible interaction among these factors are still difficult to predict. As part of this effort, the project Near-Field Processes (NF-PRO) has been focused mainly on an investigation of the combined effects of thermal, geomechanical and hydrodynamic processes on the performance of the buffer. Additionally, further studies should be undertaken for various processes such as gas transport in a buffer material, colloid formation, and, most of all, the erosion mechanism.

2.3 Backfill/Plugging

The backfill is supposed to stabilize the disposal tunnel and keep the bentonite buffer in place and prevent water ingression through the tunnel. After backfilling the disposal tunnels, plugs are installed at the end of the tunnel in order to prevent extrusion of the buffer and the backfill material into the open main tunnels. A swelling characteristic is the primary process for backfilling, just as it is for the buffer.

In host rock of clay and granite, bentonite or bentonite/crushed host rock-mixture are considered as backfill material in most national programs, while in salt systems a mixture of crushed rock salt and bentonite are likely to be used because of the cost effects in terms of material transportation for backfilling. Most of the space of the deposition tunnel should be filled with pre-compacted blocks of bentonite and crushed rock, and the gap between the stacks of blocks and the rock surface should be filled with bentonite pellets or granules. During SKB's upcoming research period, it will study the impacts of freezing and erosion on the backfill to identify changes of swelling properties. It is planned that the reference methods backfilling and plugging will have to be installed in a trial setup in the Äspö HRL before the start of construction of the HLW repository. With regards to the development of a practical technology concerning buffer construction and emplacement, Engineering Studies and Demonstration of Repository Designs (ESDRED) protocols are initiated for demonstrating the feasibility of safely disposing of radioactive wastes.

3. Geotechnical Issues in a Repository

When it comes to the reliability and the feasibility of the final disposal system, the long-term performance and safety assessment of the geological repository are of particular importance. Thus, extensive in-situ validation experiments for repository performance are necessary for filling certain technological gaps that previously existed and it is a prerequisite to establish reliable numerical models for predicting the repository performance. The European Commission (2004) reviewed the outline of international research projects for geological disposal and related key technical achievements. Tsang *et al*. (2005) presented a comprehensive comparisons of processes, parameters, and issues for Excavation-Damaged Zones (EDZ) of different rock types at different construction phases of a repository system. Research issues related to the long-term safety of engineered barrier systems and the near field are presented in Table 3 and Table 4. From the perspective of geological and geotechnical engineering, the key technical issues are discussed as follows.

3.1 EDZ and Tunnel Excavation

Table 3. Research Issue on Long-term Safety in EBS (SKB, 2004)

	Fuel	Canister	Buffer	Backfill
R (Radiological)	Radioactivity decay* Radiation attenuation/heat generation* Induced fission (criticality)*	Radiation attenuation/ heat generation*	Radiation attenuation/ heat generation*	Radiation attenuation/ heat generation*
T (Thermal)	Heat transport*	Heat transport*	Heat transport*	Heat transport*
H (Hydrological)	Water/gas transport*		Water transport unsatur.*** Water transport satur.* Gas transport/dissolution***	Water transport unsatur.* Water transport satur.** Gas transport/dissolution*
M (Mechanical)	Thermal expansion/cladding failure*	Deformation insert*** External deformation Cu** Inner deformation Cu** Thermal expansion*	Swelling* Mech. inter. buffer/backfill** Mech. inter. buffer/canister*** Mech. inter buffer/rock* Thermal expansion*	Swelling* Mech. inter. backfill/ rock*** Thermal expansion*
C (Chemical)	Advection/diffusion* Resid. gas radiolysis/oxygen form.* Water radiolysis* Metal corrosion* Fuel dissolution*** Dissolution gap invent* Speciation radionuclides/ colloid formation** Helium production*	Corrosion insert*** Galvanic corrosion* SCC insert* Radiation effects* Copper corrosion*** SCC shell*** Grain growth copper*	Advection* Diffusion* Osmosis (salt effect)** Ion exch./sorption* Montmorillonite transf.*** Dissolution/prec. impurities* Colloid release/erosion*** Radiation-induced montmorillonite transf.* Radiolysis pore water* Microbial processes**	Advection* Diffusion* Osmosis (salt effect)** Ion exch./sorption* Montmorillonite transf.* Dissolution/prec.impurities** Colloid release/erosion** Radiation-induced transf.* Radiolysis pore water* Microbial processes**
Integration		HMC evolution damaged canister***	THM evolution unsaturated*** THMC evolution saturated***	
Radionuclide transport		RN transport near-field**	Advection Diffusion** Sorption Speciation Colloid transport**	Advection** Diffusion* Sorption* Speciation*

*** : Major initiatives, ** : Moderate initiatives, * : Minor initiatives/monitoring during coming three-year period

Table 4. Research Issue on Long-term Safety in Near Field (Tsang *et al.*, 2005)

	Descriptions	Technical issues
Excavation	• Tunnel excavation • Stress redistribution • EDZ production • Drainage	• EDZ minimization • Permeability change • Anisotropy evaluation • Methods to cutoff EDZ • Tunnel sealing method • Low-pH cementitious material
Open stage	• Repository operation • Air entry resulting in oxidizing conditions • Ventilation	• EDZ Dehydration • Ventilation-induced damage • Oxidizing effects on fracture • Potentia chemical and bacterial activity
Early closure stage	• Backfill is in place • The repository is closed • Heating phase • Resaturation	• Resaturation effects • Interplay between thermal compression and resaturation • Effect of back-pressure from bentonite buffer and backfill • Chemically changing from oxidizing to reducing condtions
Late closure stage	• Slow cooling phase • Backfill and EDZ are fully saturated • Degradation of support system	• Self-sealing • Chemical and biological effect • THMC coupling reaction • Rock creep

The excavation for the final repository includes a ramp, shaft, main transport tunnel, and deposition holes. It also induces an excavation-disturbed area, which is called the EDZ and which changes the mechanical, hydrological, and geochemical properties of the rock. This change can cause unwanted structural influences on the long-term performance of the repository system: stress redistribution, additional pathways of groundwater, and, in particular, one or more orders of magnitude increase in flow permeability. Although the formation of an EDZ is inevitable, we know how to limit the extent of this zone because the magnitude of the EDZ will depend on the host rock mass condition, the method of excavation, and any mitigating strategies in the rock engineering (Hudson *et al*., 2009). Typically, among civil engineers, it is well established that the method of drill-and-blast is appropriate for hard rock, and mechanical excavation appropriate for softer rocks such as clay rock. A Tunnel Boring Machine (TBM), generally recognized to lead to the smallest EDZ in hard rock, is preferred in any type of rock formation and also in the construction of the main disposal tunnel.

Compared to the excavation of a main tunnel in a repository, a deposition hole, as shown in Fig. 2, must be excavated with tighter and narrower tolerance in the straightness and diameter of the vertical hole by considering the swelling characteristics of the bentonite buffer. In order to minimize the formation of an EDZ in the surrounding rock, the bottom of the deposition hole should be as flat as possible. A feasibility study was carried out in SKB (2007) dealing with different possible technologies: reverse raise boring, use of a Shaft Boring Machine (SBM) or TBM, water clusters, air clusters, water jets, and core drilling. From the result of the feasibility tests, reverse raise boring was selected as a reference method that satisfied the final repository requirements, including the trial boring of three deposition holes in POSIVA (Nuclear Waste Management Expert in Finland)'s investigation tunnel for the VLJ (reactor waste) repository (Autio and Kirkkomäki, 1996) and in horizontal deposition tunnels for KBS-3H in Äspö HRL (Bäckblom and Lindgren, 2005). In the research for a specific design of a reverse raise boring system, the researchers started to manufacture a prototype machine. Furthermore, the development of an alternative type of water jet and core drilling will follow over the next few years.

There are a large number of EDZ research studies available in the literature. For example, the EDZ affects the performance of radioactive waste geological repositories (Tsang *et al*., 2005). Meanwhile, the EDZ has no impact on the operational safety of repositories, but, for long-term performance, the EDZ pathway may be important for potential radionuclide migration (i.e., hydro-thermo-mechanical coupling reaction; Davies and Bernier, 2005). For enhanced understanding and prediction of the long-term behavior of a repository, the assessment of the time-dependent evolution of the EDZ (that is, reversibility) and property changes under the aforementioned coupled reactions coming from water saturation, temperature gradient, and buffer swelling still remains to be done, as challenge of our geotechnical engineering knowledge that must be met. At present, further research topics in the context of repository construction include stabilization, ventilation and drainage, waste transportation, and waste emplacement equipment.

3.2 Optimization of Cementitious Material

Generally, it is difficult to construct a geological repository without the use of cementitious materials, at least for the constraint of water ingress, access tunnel floors, plugging of backfill, and the sealing of tunnels from water flowing into the HLW repository. To minimize the environmental impact and influence of cementitious materials, the development of optimized cement is indispensable; research into its field applications and a long-term performance assessment are necessary. As part of an effort to optimize the cementitious materials, studies related to the development and validation of low pH grout have been carried out actively in both the laboratory and the field (e.g., Kronlöf,

Table 5. Low pH Cement Recipe Currently under Investigation

Country	Cement composition	Developed materials
Canada-AECL	OPC 50%-SF 50%	High strength concrete
Finland-POSIVA	OPC 60%-SF 40%	Injection grout
France-ANDRA, CEA, EDF	OPC 60%-SF 40%	High strength concrete
Japan-JAEA, CRIEPI, NUMO	OPC 40%-SF 20%-FA 40% OPC 37.5%-SF 32.5%-FA 30% OPC 20%-SF 32.5%-BFS 47.5% OPC 33%-BFS 13.5%-FA 13.5%-SF 40%	Shotcrete High strength concrete
USA-ORNL	OPC 40%-BFS 30%-FA 25%-SF 5%	Shotcrete High strength concrete
Spain-IETcc-CSIC, ENRESA	OPC 60%-SF 40% OPC 35%-SF 35%-FA 30%	Shotcrete
Switzerland- NAGRA	OPC 60%-SF 40%	Shotcrete

OPC: ordinary portland cement, SF: silica fume, FA: fly ash, BFS: blast furnace slag

Table 6. Functional Requirements of Low pH Cement for Grout and Shotcrete (Grout-Kronlöf, 2005; Shotcrete-Fernandez *et al.*, 2005)

Grout	
Property	Requirement
pH	≤ 11
Penetration bmin Penetration bcrit Viscosity	≤ 80 μm ≤ 20 μm ≤ 50 mPa
Bleed	≤ 10%
Workability time Shear strength Yield value	≥ 60 min ≥ 500 Pa ≤ 5 Pa
Compressive strength	≥ 4 MPa
Shotcrete	
Property	Requirement
Maximum pH	≤ 11
Hydraulic conductivity	K<10-10 m/s
Young's Modulus Poisson ratio Tensile strength Friction angle Cohesion Compressive strength	< 20 GPa 0.2~0.3 1 MPa > 37°C 2 MPa 30 MPa
Workability	> 2h
Pumpability	500 m
Peak of hydration	< 40°C

2005; Sievänen *et al.*, 2006; Bodén and Sievänen, 2006) because conventional cement of high pH can accelerate the release of uranium, increase the mobility of uranium, fission products, and actinides, and change the solubility of bentonite, which reduce the effectiveness of the buffer materials.

Low pH grout/shotcrete has been studied since 2002 in a joint project among SKB, POSIVA, and NUMO (e.g., Bodén and Sievänen, 2006). The development of low pH cement has been a primary subject in the construction of a repository among the countries that are interested in final disposal (Table 5). The pH criterion has been specified and the properties of low pH grout mix have been optimized (e.g., Orantie and Kuosa, 2007). Additionally, the functional requirements for low pH grout have been established, as summarized in Table 6. SKB and POSIVA defined a pH limit of < 11 for low pH cement grout leachates. To attain this pH requirement, blending agents should comprise at least 40 wt% of the dry materials and the Ca/Si ratio, primarily formed as Calcium Silicate Hydrate (CSH) gel, should be under 0.8. Silica Fume (SF) as a blending agent is considered to be the most promising agent for low pH grouts of repositories (Torbjörn *et al.*, 2005). When adding SF to enhance cement quality, there arises a need for high water content in the cement paste. Then, it is necessary to use additives such as super-plasticizers to improve the workability of the low pH cement. Currently, it should be noted that large fractures (> 100 μm) will be grouted with low-pH cement material and small fractures (< 100 μm) with non-cementitious grout such as silica sol for sealing the fractured rock mass.

As part of the in-situ tests for the validation of low-pH cement, there have been extensive field experiments: a Tunnel Sealing Experiment (TSX) for a concrete bulkhead in Canada's URL, grout tests in Helsinki and Onkalo (Finland), a shotcrete test at the Hagerbach Test Gallery (Switzerland), a short plug test at the ÄSPÖ URL (Sweden), and a long plug test at the GRIMSEL URL (Switzerland). Validation experiments are being actively carried out within the program of the international cooperative research project, the ESDRED (Module #4). Recently, subsequent research projects, such as the Long-term Cement Studies (LCS) at Grimsel Test Site (GTS, Switzerland), the JAEA Grouting Project (JGP) in Japan, and the Cement-clay Interaction (CI) at Mont Terri (Switzerland), have been newly started.

Low-pH cement has been developed and confidence in material strength, workability, viscosity, bleeding and setting time are high. However, there is little information on the long-term performance of cementitious materials, especially concerning durability and ensuring of a watertight repository structure for over 100 years. Thus, more study should be focused on the long-term performance characteristics, interactions of the bentonite buffer material with high pH plumes, effects of the migration/sorption of radionuclides, and numerical modeling of total performance.

3.3 Long-term Gas Migration

In a deep geological disposal repository, gases such as hydrogen (H_2), methane (CH_4), and carbon dioxide (CO_2) can be produced around the EBS and in the near field area by anaerobic corrosion, microbial degradation of metallic materials, and degradation of organic wastes. Cementitious materials possibly used for sealing and tunnel supports can be a potential source of carbon dioxide after the degradation process. Fig. 3 shows potential sources of gas production and migration paths through the engineered barrier and near field. Dissolved gas produced inside a canister when it has contact with water is transported through the bentonite buffer. This causes the pressure to increase not only between the canister and the buffer but also between the buffer and the near field rock mass, which subsequently gives rise to negative consequences for the performance of the repository. With regard to gas migration, the key issues are the minimum pressure gas will enter the bentonite or host rock, mechanism controlling gas entry, its preferential pathways, and how much the barrier is influenced etc.

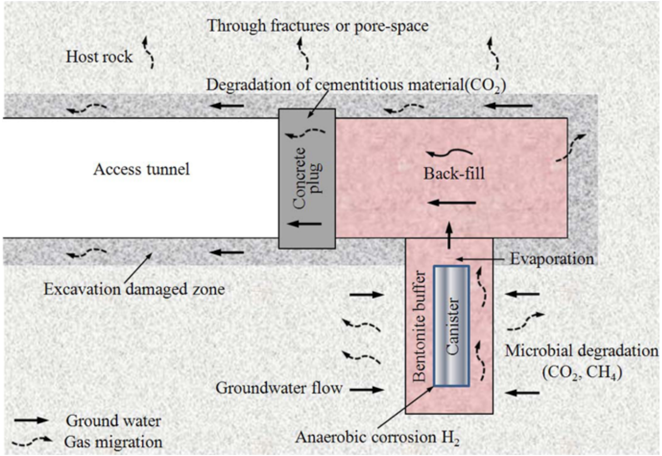


Fig. 3. Potential Sources of Gas Production and Migration Paths

The primary works of research in the literature concerning gas invasion through compacted bentonite are listed in Table 7. One gas injection apparatus which was recently used for gas migration study in a laboratory is shown in Fig. 4. Gas will enter the buffer when the pressure produced within the canister exceeds the entry pressure of the bentonite. Isotropically-consolidated bentonite shows that gas breakthrough occurs at a pressure slightly greater than the sum of the swelling pressure and the pore-water pressure. There is a close correlation between the gas entry pressure and the bentonite swelling pressure for compacted clays or rather between gas entry pressure and total stress (swelling pressure

Table 7. Summary of Experiments on Gas Migration in Compacted Bentonite (Hoch *et al*., 2004)

Authors	Bentonite	Dry density (Mg/m^3)	Flow geometry	Gas flow controls	Confining conditions
Pusch and Forberg (1983)	Mx80	~1.35 - 1.65	Linear	Constant pressure/ pressure increments	Constant volume oedometer
Pusch *et al*. (1985)	Mx80	~1.1 - 1.78	Linear	Pressure increments	Constant volume oedometer
Horseman and Harrington (1997)	Mx80	1.5 - 1.7	Linear(axial) flow	Displacement of gas by water from an upstream reservoir	Constant isotropic stress in flexible sleeve subject to external fluid pressure (8-22 MPa)
Horseman *et al*. (1997)	Mx80 paste	1.3 - 1.4	Point source and sink	Displacement of gas by water from reservoir	Cylindrical pressure vessel with confining pressure (0.8- 2.7 MPa) imposed on floating end cap
Tanai *et al*. (1997)	Kunigel VI, Fo -Co clay	1.4 - 1.8	Linear	Pressure increments	Constant volume cylinder
Gallé (1998, 2000)	Fo-Co clay	1.6 - 1.9	Linear	Pressure increments	Constant volume oedometer cell
Graham *et al*. (2002), Hume (1999)	Avonlea	0.6 - 1.4	Linear	Pressure increments	Constant volume oedometer cell
Harrington and Horseman (2003)	Mx80	1.577, 1.582	Approximately radial from central source	Displacement of gas by water from an upstream reservoir	Constant volume cylindrical vessel
Harrington and Horseman (2003)	Mx80	1.596	Linear	Displacement of gas by water from an upstream reservoir	Cylindrical pressure vessel with confining pressure (10 MPa) applied to floating end caps
Tanai (2002)	Mx80	1.63	Linear	Constant gas pumping rate	Constant isotropic stress in flexible sleeve subject to external fluid pressure

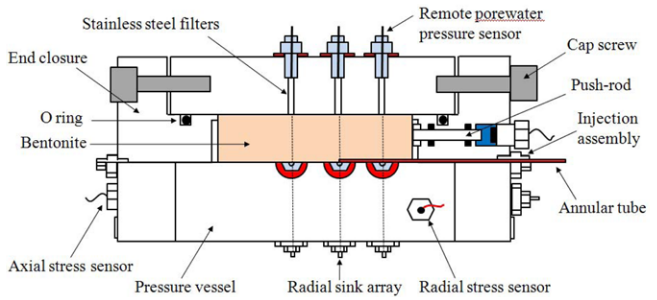


Fig. 4. Gas Migration Apparatus for Constant Volume and Radial Flow (after Harrington and Horeseman, 2003)

plus the external pore-water pressure) (Pusch *et al*., 1985 and Horseman and Harrington, 1997). The stress condition will influence the mode of gas migration and the direction that gas migration pathways might take. Although gas migration mechanisms are still not clearly understood and there are uncertainties and inconsistencies in the experimental data, there are three possible mechanisms of gas migration that have been proposed so far (Hoch *et al*., 2004): (1) gas migration by displacement of water from the pores of the bentonite; (2) gas migration through the creation of gas pathways by microfissuring that is produced from the disturbance of the clay structure; and (3) gas migration by macroscopic fracturing of the clay specimens.

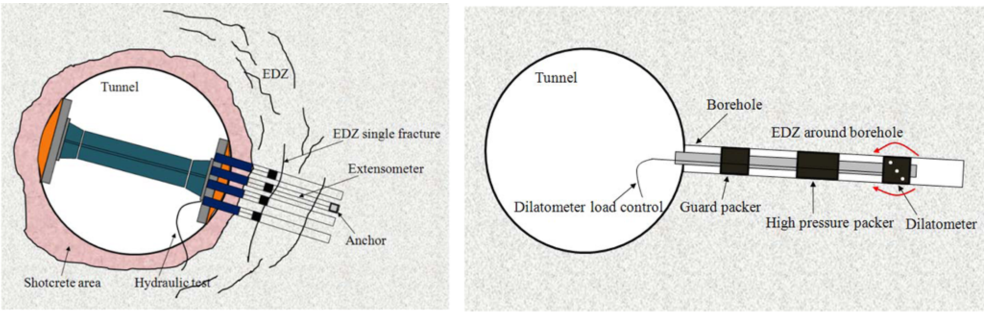
There was an in-situ Large Scale Gas Injection Test (LASGIT) at a KBS-3 deposition hole in the Äspö HRL as part of a European Community co-funded project. At the Grimsel Test Site (GTS) in Switzerland, two research projects related to gas migration were carried out in GTS Phase *V* projects (1997-2004): One was a gas migration test in an EBS and near field while the other was for gas migration in the shear zones in the far field.

It has been noted that gas migration is not an independent technical issue but one interrelated with the performance assessment of a disposal system. Gases like hydrogen and carbon dioxide produce pressure-induced pathways in a bentonite buffer, affect the effective stress condition and local pore water pressure inside the buffer, and cause additional radionuclide release by forming a possible preferential pathway for groundwater. Subsequently, this can make more complicated EDZ issues. For example, a gas pressure-induced fracture opening is interrelated with the chemical/bacterial interaction processes in micro-cracks of the EDZ. Thus, it is important to make sure that gases escape without damaging the buffer or rock mass.

3.4 Self-Sealing/Healing

Sealing is a reduction of fracture permeability/transmissivity of a rock mass by any hydromechanical, hydrochemical, or hydrobiochemical processes; healing means a phenomenon of structural and mechanical homogenization of a rock mass in addition to sealing (Bastiaens *et al*., 2007). After closure of a repository system, backfill and EDZ start to be resaturated. On the order of 100 years or more, the properties of the rock mass will be changed by self-sealing/healing of rock fractures in the excavation-damaged zone in combination with heat, groundwater, stress, and biological and chemical activity. It has been shown that the sealing process of the fractures present in the EDZ leads to a reduction of the hydraulic conductivity in the near field rock mass. Self-sealing/healing of the EDZ in a rock mass with time is generally produced by dilatancy, creep, disintegration, swelling of backfill/plugging, reconsolidation, and newly formed minerals after the closure stage of a repository when the system becomes fully saturated with groundwater (Bernier *et al*., 2007; Bastiaens *et al*., 2007).

The SELFRAC of EC project (2001-2004; Bernier *et al*., 2007) is one of the projects that have actively studied the fracturing and self-healing processes of EDZs in the laboratory and in in-situ experiments including numerical modeling to assess impact on the long-term performance of repositories. In-situ experiments in the SELFRAC were performed both at Mont Terri (Switerzerland) and at HADES (Belgium). A series of experiments are being actively conducted at the Mont Terri underground laboratory in Switzerland (Fig. 5). The project results (e.g., Boom clay and Opalinus clay) clearly show that the sealing process was preferable to the healing process, in which swelling, consolidation, and creep were considered to be the main mechanisms (Bastiaens *et al*., 2007). In the framework of Phase 15 (2009-2010) at the Mont Terri Project, additional experiments are being carried out



(a) (b)

Fig. 5. Fracture Self-sealing Test on Excavation-damaged Zone: (a) Long-term Plate Loading Test (after Heitz *et al*., 2003), (b) Long-term Dilatometer Test (after Bühler, 2005)

to improve the existing THMG models: self-sealing barriers of clay/sand mixture and self-sealing in combination with heat.

Self-sealing/healing reduces the fracture permeability and probably results in an increase of strength in the EDZ. However, there is a concern that the process highly depends on the rock type and heterogeneity in the rock properties. It usually occurs in clays or salt rather than crystalline rock after closure of a repository (Tsang *et al*., 2005). Because there have been few long-term experiments for the self-healing effect, the process is still not fully understood. The evaluation method of sealing properties is primarily limited to the measurement of permeability and porosity or to a mineralogical survey. The adoption of more advanced geophysical monitoring techniques such as acoustic emissions shows promising potential for dynamic analysis. Thus, one needs to pay attention to self-healing characteristics for different host rock types and further to investigate its long-term behavior with more advanced monitoring techniques for a better understanding of the performance of repository systems in different geological formations.

4. Numerical Modeling Issue: Coupled THMG

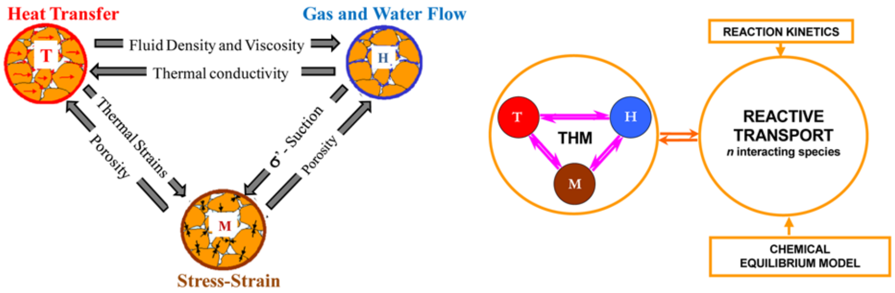
Numerical modeling is a key component in the design of a nuclear waste disposal. Numerical models are crucial tools in the long-term performance analyses and safety assessment of a geological repository for HLW (as introduced in section 3). Numerical models are very useful tools for exploring different geological disposal concepts (see section 2) and possible scenarios in a comprehensive, rapid and economical manner. Furthermore, the numerical model is an instrument that allows the integration of all the components of a nuclear waste disposal (presented in Sections 2 and 3).

A theoretical formulation is an appropriate way to integrate the relevant THMG phenomena (described in Section 1) in a consistent and unified framework. In a coupled formulation, the roles of the various physical phenomena and their mutual relationships are clearly expressed with no ambiguity. Once implemented numerically, the mathematical formulation can be used to achieve a better understanding of the interaction between the different THMG phenomena. Indeed, it will be an essential tool for the design of repositories, especially considering that very long-term predictions (involving sometimes hundreds and thousands of years) are generally required in these analyses. Such numerical tools have to be validated before they are actually used to assist the design of HLW disposal. Properly instrumented full scale in-situ tests are important in this aspect. In the last few years, several full-scale tests have been carried out aimed at advancing the current knowledge about the behavior of this kind of system and to demonstrate the feasibility of different conceptual designs (e.g. Huertas *et al*., 2006; Volckaert *et al*., 2000; Dixon *et al*., 2002; Svemar *et al*., 2002; Gens *et al*., 2009; Martin and Barcala, 2005). These tests have also provided the opportunity to validate the computer codes used in the numerical analysis. This section presents the coupled THMG phenomena that generally take place in porous media subjected to heating and hydration.

4.1 Coupled THMG Phenomena

THMG phenomena in the near field are strongly coupled. Fig. 6 schematically illustrates the main physical phenomena, with their mutual interactions, that take place in a porous medium subjected to simultaneous THM solicitations. For example, within the thermal phenomena (T), heat storage is strongly affected by hydraulic phenomena (H) via fluid flow (i.e., liquid and gas movements change the amount of water and air present in the porous medium), and by the mechanical problem (M) via porosity changes (which modify the amount of space left for fluids). Phase changes also modify heat storage through the latent heat of vapor.

Heat conduction is driven by temperature gradients (through Fourier's law). Thermal conductivity depends on the partial saturation of the phases (which are mainly controlled by liquid and gas flow) and porosity variations (which are related to stress/strain changes). Within the hydraulic phenomena (H), water storage is affected by the thermal problem through the dependence of liquid and vapor density on temperature. Phase change modifies the amount of water in liquid and gas phases. Water storage is also affected by the mechanical problem, as



(a) (b)

Fig. 6 THM and Chemical Analyses: (a) Porous Medium: Main Thermo-Hydro-Mechanical Phenomena in and their Mutual Interactions, (b) Inclusion of Geo-chemical Effects in Coupled THM and Chemical Analysis porosity changes modify the space available for the flow of liquid and gas. Liquid water transfer is mainly controlled by liquid pressure gradients (through Darcy’s law). Hydraulic conductivity is mainly affected by liquid viscosity (that diminishes with temperature), porosity changes (controlled by the mechanical problem), and degree of saturation, which varies with temperature (due to thermal expansion and phase changes).

4.2 Coupled Mathematical Formulation

A large number of THMG phenomena and interactions can potentially occur in a porous medium subjected to multi-physical actions. It is difficult to include all of them in the coupled analysis. Therefore, a crucial step before developing the mathematical framework is to select the key phenomena to be considered in the numerical analysis. It is also recommendable to develop the mathematical formulation, and the associated computer code, in such a way that future upgrades can be implemented with a minimum effort when new experimental data or evidence require them. Some of the basic THMG phenomena to be considered in a standard THMG formulation are listed below:

- Heat transport: heat conduction, heat convection (liquid water), heat convection (water vapor), phase changes
- Water flow: liquid phase properties, water vapor diffusion
- Air flow: gas phase properties, air solution in water, dissolved air diffusion
- Mechanical behavior: thermal expansion of materials, behavior of geo-materials dependent on stresses, fluids pressures, and temperature
- Geochemical actions: chemical reactions in the liquid phase, cation exchange, dissolution/precipitation of minerals, adsorption

The majority of the mathematical formulations and associated computer codes recently developed by geo-engineers to perform coupled THM analyses (e.g., Gawin *et al.* 1995; Olivella *et al.*, 1994, 1996; Thomas and He, 1995; Collin *et al.*, 2002; Rutqvist *et al.*, 2005) consider the main phenomena listed above. As for the inclusion of geochemical effects in coupled analysis, the first developments considered conservative transport phenomena only (e.g. Thomas and Cleall, 1998); more recently, reactive transport equations have been coupled with THM formulations (Guimarães *et al.*, 1999; Thomas *et al.*, 2001; Guimarães *et al.*, 2007). As an example of the approaches quoted above, the coupled THM formulation proposed by Olivella *et al.* (1994), and the finite element program CODE_BRIGHT (Olivella *et al.*, 1996) based on this formulation will be briefly introduced herein. Both the formulation and the code have been extensively validated and used to solve a variety of coupled THMG problems in geotechnical engineering. The approach is composed of three main parts: balance equations, constitutive equations, and equilibrium restrictions. The framework is formulated using a multi-phase, multi-species approach where the subscripts identify the phase (“s” for solid, “l” for liquid and “g” for gas) and the superscript indicates the species (“‘h” for mineral, “w” for water and “a” for air). It is assumed that the liquid phase may contain water and dissolved air, and the gas phase may be a mixture of dry air and water vapor. Dry air is considered as a single species. A detailed description can be found elsewhere; a brief description of some components of the formulation is included below.

4.2.1 Balance Equations

Mass balance equations are established following the compositional approach, which consists of balancing the species rather than the phases. For example, the total mass balance of water is expressed (Olivella *et al.*, 1994) as follows:

$$\frac{\partial}{\partial t}(\theta_l^w S_l \phi + \theta_g^w S_g \phi) + \nabla \cdot (\mathbf{j}_l^w + \mathbf{j}_g^w) = f^w \tag{1}$$

where θ_l^w and θ_g^w are the masses of water per unit volume of liquid and gas respectively; ϕ is the porosity; S_l and S_g represent the volumetric fraction of pore volume occupied by liquid and by gas (degree of saturation for their respective phases); $\mathbf{j}_l^w$ and $\mathbf{j}_g^w$ denote the total mass fluxes of water in the liquid and gas phases (water vapor), with respect to a fixed reference system; and f^w is an external supply of water. A similar equation can be written for the air: in this case the gaseous phase is assumed to be a mixture of air and water vapor. The mass balance of solids is also established for the whole porous medium and this equation is mainly used to account for the porosity changes.

The balance of energy is proposed for the whole medium and thermal equilibrium between phases is assumed; consequently, only one equation is required to establish the energy balance. This hypothesis is justified considering the low permeability of the expansive clays. The total internal energy per unit volume of porous media is obtained by adding the internal energy of each phase corresponding to each medium. As for equilibrium, the balance of momentum for the porous medium reduces to the equilibrium equation in total stresses as no inertial effects are considered. Through an adequate constitutive mechanical model, the equilibrium equation is transformed into a form expressed in terms of solid velocities and fluid pressures. The assumption of small strain rate is also made.

Reactive transport equations can be coupled with the THM formulation. Considering the reactive transport of N chemical species in a deformable unsaturated porous medium, the transport of every species can be expressed (Guimarães *et al.*, 2007) as follows:

$$\frac{\partial}{\partial t}(\phi S_l \rho_l c_i) + \nabla \cdot \mathbf{j}_i = R_i \quad (i=2, ..., N) \tag{2}$$

where c_i is the concentration of species i in moles/Kg of solution, R_i is the total production rate of species i due to chemical reactions in moles/m^3/s, and j_i is the total flux of species i in moles/m^2/s. This flux is considered as the sum of advective and non-advective fluxes (Olivella *et al.*, 1994). Advective flux is, in turn, the sum of the movement of the liquid phase with respect to the solid phase

4.2.2 Constitutive Equations and Equilibrium Restrictions

The constitutive equations establish the link between the main unknowns (e.g., displacements, fluid pressures, temperature and solute concentrations) and the dependent variables (e.g. stresses, fluxes and degree of saturation). There are also two main equilibrium restrictions: the psychrometric law (which controls the amount of water vapor in the gas phase); and Henry's law (which controls the amount of air dissolved in water). Due to space limitations, the constitutive equations are not presented in this paper; details can be found elsewhere (e.g., Gens *et al*., 2009; Sánchez *et al*., 2010). A summary of the main constitutive equations used in the coupled analysis for radioactive waste disposal is listed in Table 8. Specific laboratory tests should be performed to indentify the model parameters of the different constitutive laws. The model parameters listed in Table 8 correspond to FEBEX bentonite. Notation is presented in Table 9. Fig. 7 presents the more relevant main constitutive laws alongside the experimental data used to determine the model parameters.

As for the mechanical behavior, the geo-materials that make up the repository near field will be subjected to temperature and fluid pressures changes under practically confined conditions. They may be also partially saturated at some stages of the analysis and the generalized stress path could go beyond the elastic domain. These geo-materials can also react chemically with the pore water during the repository lifetime. Therefore, a very general framework able to describe the mechanical behavior considering unsaturated and non-isothermal conditions for chemically actives soils will be desirable for this kind of analysis. To deal with this problem, a general framework has been developed based on the elasto-plastic Barcelona Basic Model (BBM) for unsaturated soils (e.g., Alonso *et al*., 1990).

The BBM has then been extended for non-isothermal conditions (e.g., Gens, 1995) and expansive soil behavior (e.g. Gens and Alonso, 1992; Sanchez *et al*., 2005, 2008). The influence of osmotic suction and exchangeable cations has been recently included in this formulation to account for chemical effects on expansive soil behavior (Guimarães *et al*., 2009). The main equations of the BBM are also presented in Table 8.

Table 8. Summary of Constitutive Laws and Equilibrium Restrictions

Equation	Variable name	Equation	Parameter relationships	Parameters
Constitutive equations				
Darcy' laws	Liquid and gas advective flux	$\mathbf{q}_\alpha = -\mathbf{k}\frac{k_{r\alpha}}{\mu_\alpha}(\nabla P_\alpha - \rho_\alpha \mathbf{g}) \quad \alpha = l, g$	$\mathbf{k} = k_0 \frac{\phi^3}{(1-\phi)^2} \frac{(1-\phi_0)^2}{\phi_0^3}\mathbf{I} \quad k_{rl} = S_e^n$	k_0=1.9 e^{-21} m^2; $\phi_0 = 0.40$; $\phi = 3$
Fick's law	Vapour non advective flux	$\mathbf{i}_g^w = -(\phi\rho_g S_g \tau D_m^w \mathbf{I} + \rho_g \mathbf{D}'_g)\ \nabla\omega_g^w$	$D_m^w = 5.9\times10^{-12}\frac{(273.15+T)^{2.3}}{P_g}$	$\tau = 0.8$
Fourier's law	Conductive heat flux	$\mathbf{i}_c = -\lambda\nabla T$	$\lambda = \lambda_{sat}^{s_e}\lambda_{dry}^{(1-s_e)}$	$\lambda_{sat} = 1.15$ $\lambda_{dry} = 0.47$
Retention curve	Phase degree of saturation	$S_e = \left[1+\left(\frac{s}{P_0}\right)^{\frac{1}{1-\lambda_0}}\right]^{-\lambda_0}\left(1-\frac{s}{P_d}\right)^{\lambda_d}$	$S_e = \frac{S_l - S_{lr}}{S_{ls} - S_{lr}} \quad S_l = 1 - S_g$	$P_0 = 28$ MPa; $\lambda = 0.18$ $P_d = 1100$ MPa; $\lambda_d = 1.1$
Mechanical Constitutive Model	Stress Tensor	$\dot{\sigma} = \mathbf{D}_{ep}\cdot\dot{\varepsilon}+\gamma_s\dot{s}+\gamma_T\dot{T}\,;\ \frac{\dot{P}_0^*}{P_0^*} = \frac{(1+e)}{(\lambda_{(0)}-\kappa)}\dot{\varepsilon}_v^p$ $\dot{\varepsilon}_v^e = \frac{\kappa}{(1+e)}\frac{\dot{p}}{p}+\frac{\kappa_s}{(1+e)}\frac{\dot{s}}{(s+0.1)}$ $+(\alpha_0+\alpha_2\Delta T)\,\dot{T}$	$F = \frac{3J^2}{g_y^2} - L_y^2(p+P_s)(P_o-p) = 0\,;\ p_0 = p_c\left(\frac{p_{0T}^*}{p_c}\right)^{\frac{\lambda_{(0)}-\kappa}{\lambda_{(s)}-\kappa}}$ $p_s = ks\ e^{-\rho\Delta T}\,;\ p_{0T}^* = p_0^*+2(\alpha_1\Delta T+\alpha_3\Delta T\lvert\Delta T\rvert)$ $\lambda_{(s)} = \lambda_{(0)}[r+(1-r)\exp(-\zeta_s)]$ Mechanical model from Alonso *et al*. (1990) & Gens (1995)	$\kappa = 0.04$; $\lambda_{(o)} = 0.14$ $P_o^* = 14$ MPa $r = 0.75$; $\zeta = 0.05$ $p_c = 0.10$ MPa; $M = 1.5$ $k = 0.1$; $\nu = 0.4$ $\alpha_1 = 1.5\times10^{-4}$ [1/C]; $\rho = 0.2$
Phase density	Liquid density Gas density	$\rho_l = 1002.6\exp(4.5\times10^{-4}(P_l-0.1)-3.4\times10^{-4}T)\,;\quad \rho_g =$ ideal gas law		
Phase viscosity	Liquid viscosity Gas viscosity	$\mu_l = 2.1\times10^{-12}\exp\left(\frac{1808.5}{273.15+T}\right)\,;\ \mu_g = 1.48\times10^{-12}\exp\left(\frac{(273.15+T)^{1/2}}{1+\frac{119}{(273.15+T)}}\right)$		
Equilibrium restrictions				
Henry's Law	Air dissolved mass fraction	$\theta_l^a = \omega_a^l\rho_l = \frac{P_a}{H}\frac{M_a}{M_w}\rho_l$		
Psycho-metric Law	Water vapour dissolved mass fraction	$\theta_g^w = (\theta_g^w)^0\ \exp\left(\frac{\Psi M_w}{R(273.15+T)\rho_l}\right)$	$(\theta_g^w)^0 = \frac{M_w P_{v(T)}}{R(273.15+T)}$	

Table 9. Notation for Numerical Modelling

α	subscript identify the phases: liquid (l) & gas (g)	e	void ratio
α_0	parameter for elastic thermal strain	F	*BBM* yield surface
α_1	parameter that relates p_o^* with T	g	a lode angle function
α_2	parameter for elastic thermal strain	$\mathbf{I}$	identity matrix
α_3	parameter that relates p_o^* with T	i	superscript identify the species: air (a), water (w) & solid (s)
ΔT	temperature increment ($T-T_0$)	$\mathbf{i}_\alpha^i$	non-advective mass flux (i=w, a ; α=l, g)
ε	strain vector.	$\mathbf{i}_c$	non-advective heat flux
$\dot{\varepsilon}^e$	elastic strain increment due to stress changes	J	2nd stress invariant of deviatoric stress tensor
$\dot{\varepsilon}_s^e$	elastic strain increment due to suction changes	$\mathbf{j}_{E\alpha j}$	advective energy flux in α phase
$\dot{\varepsilon}_T^e$	elastic strain increment due to T changes	$\mathbf{j}_\alpha^i$	total mass flux respect to a fixed system
ε_v^p	total plastic volumetric strain	K	bulk modulus
κ	elastic stiffness parameter for changes in p	K_s	bulk modulus for changes in suction
κ_s	elastic stiffness parameter for changes in suction	K_T	bulk modulus for changes in temperature
λ	thermal conductivity	k_0	the intrinsic permeability at a reference porosity
$\lambda_{(s)}$	compressibility parameter for changes in net mean stress for virgin states of soil at suction s	ϕ-	porosity
$\lambda_{(s)}$	compressibility parameter for changes in net mean stress for virgin states of soil at suction s	k	parameter describing the increase in cohesion with suction
λ_o, λ_d	retention curve parameters	n	relative permeability parameter
μ	poisson's coefficient	p	mean net stress
μ_α	dynamic viscosity of α phase ($\alpha = l, g$)	p_c	reference stress
θ_α^i	fraction mass (species/phase) per unit vol. phase	p_0	net mean yield stress at current suction and temperature
ω_α^i	mass fraction of i-species in α phase	p_0^*	net mean yield stress for saturated conditions at reference temperature
ρ	parameter that relates cohesion and T	p_{0T}^*	net mean yield stress for saturated conditions at current temperature
ρ_s	solid density	p_r	reference stress
ρ_α	mass of α phase per unit of volume of α phase	P_0, P_d	retention curve parameters
$\boldsymbol{\sigma}_t$	total stress vector.	$\mathbf{q}_\alpha$	volumetric flux of phase respect to the solid
$\boldsymbol{\sigma}$	net stress vector ($\boldsymbol{\sigma}_t - \mathbf{I}p_g$)	r	parameter defining the minimum soil compressibility
ζ	parameter controlling the rate of increase of soils stiffness with suction	s	matric suction ($p_g - p_l$)
$\mathbf{D}_\mathrm{e}$	elastic matrix	S_α	volumetric fraction of pore volume occupied by α phase.
$\mathbf{D}_\mathrm{ep}$	elasto-plastic matrix	T	temperature (T_0= reference temperature)
$\mathbf{D}_\alpha^i$	dispersion tensor of the medium		

4.2.3 Numerical Approach

To solve the problem numerically, one unknown "state variable" is associated with each of the balance equations mentioned above. For example, liquid pressure (P_l) is associated with gas pressure (P_g) with the air mass balance equation, temperature (T) with the energy balance equation; displacements field (u) with the momentum balance equation. These PDEs (Partial Differential Equations) can be implemented in the finite element program CODE_BRIGHT. All the equations are solved simultaneously in a fully coupled way. CODE_BRIGHT is a tool designed to analyze coupled THM problems in geological media. From state variables, dependent variables are calculated using the constitutive equations or the equilibrium restrictions (CODE_BRIGHT User's Manual, 2010).

5. Other Emergent Issues

After closure of a repository system, resaturation of EBS components and EDZ will probably occur. Due to the high decay heat of nuclear waste, however, there is a tendency toward dehydration at the interface between waste canisters and the bentonite buffer, which causes stress redistribution inside the buffer and may induce the vapor to flow outward into the near field. This interaction (i.e., between resaturation and temperature

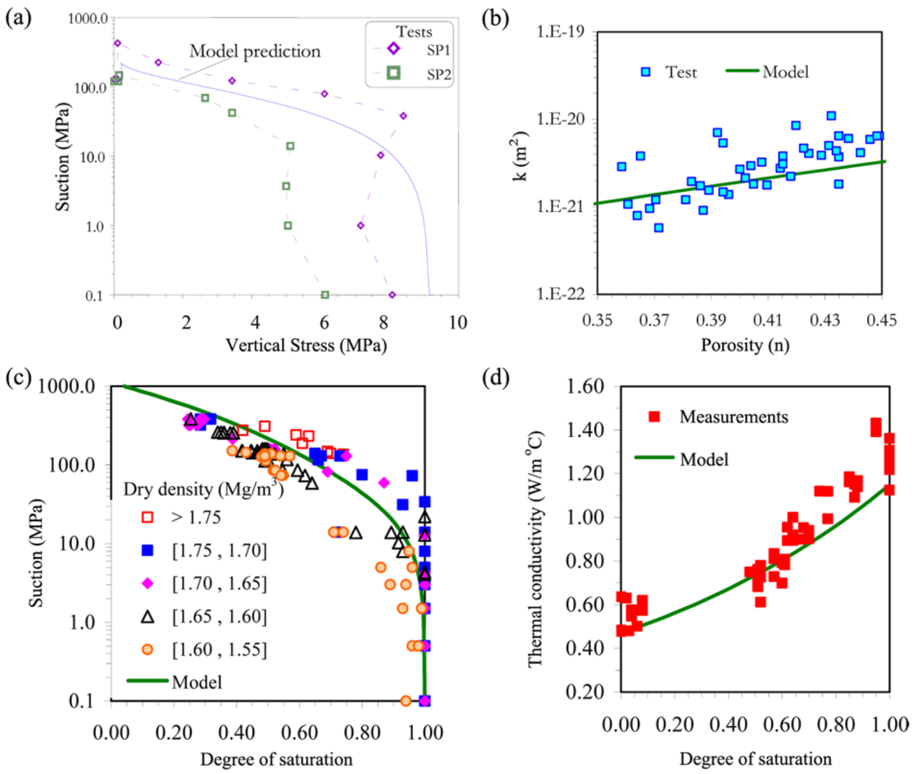


Fig. 7. Main Constitutive Laws: (a) Computed Stress Path for Swelling Pressure Tests using the BBM (Experimental results (SP1 and SP2 paths) are provided for comparison.), (b) Variation of Saturated Permeability with Porosity (Experimental data and adopted model for the intrinsic permeability law.), (c) Retention Curve Adopted in the Analyses, Together with the Experimental Data for FEBEX Bentonite (Symbols), (d) Thermal Conductivity: FEBEX Bentonite Experimental Results (Symbols) and Model Fitting

gradient) changes the distribution of water content, which would have significant dynamic impact on the behavior of the EDZ (Tsang *et al*., 2005), and can be a notable factor that makes the performance assessment of a repository system more complicated, in addition to other factors such as the deep geological conditions and the extremely long containment time of a repository. These factors present the main challenge to geotechnical engineers from the aspect of the sustainable development of nuclear energy.

Besides the geotechnical issues described in the previous sections, there still remain a lot of emergent geotechnical research challenges to be met in order to achieve an increase in the reliability of radioactive waste repository design, as follows:

- Natural analogue studies for extremely long-term evaluation
- Radionuclide migration studies
- Long-term chemical and microbial activity
- Canister corrosion issues
- Ventilation optimization during operation phase
- Interactions of EBS components and EDZ
- Anisotropic behaviors of EDZ
- More advanced monitoring techniques
- Improvement of mathematical models for full integration of coupled reaction

As a radioactive waste repository is usually under extreme conditions, most of its geotechnical issues and challenges are considered as critical and emergent issues. Thus, some knowledge and lessons gained during the design and construction of a radioactive waste repository can be directly/indirectly applied to emerging geotechnical research areas such as CO_2 sequestration/storage and underground oil storage, etc.

A full integrated evaluation of all conditions is not necessary; in reality, it is not possible to conduct a full evaluation of the reliability of a radioactive repository. However, a high level of understanding of EBS components and primary reaction processes is necessary for enhanced performance assessment and prediction of the short- and long-term behavior of a radioactive repository system. Thus, a multidisciplinary approach bringing in the various fields of engineering and science, for instance, advanced geophysical sensing/monitoring techniques or biotechnology, etc. is highly recommended to provide more reliable information than has been known or identified before.

6. Conclusions

This paper introduced an overview of deep geological disposal concepts based on Finnish, Swedish, and Spanish disposal programs, in which countries the associated R&D programs are most actively conducted. The paper discussed emergent and important research issues to be solved in the context of geotechnical engineering and presented a state-of-the-art numerical modeling of the coupled THMG process in a radioactive repository. The deep geological conditions of a repository, the extremely long containment time, and the characteristics of nuclear waste itself can be characterized as salient features from the geological and geotechnical aspects of a repository system. The complex circumstance of these critical conditions assigns more challengeable missions to geotechnical engineers.

Recently, there has been a tendency to adopt a delayed approach (phasing) for waste disposal management options. Retrievability, long-term underground storage, and interim storage are under discussion as radioactive waste management options, all of which are highly influenced by social, political or economic concerns. Even if an alternative management option is adopted rather than the geological disposal concept, however, the introduction of such a new option would result in increased requirements for the geomechanical stability of open spaces and the safety issues in a radioactive repository. Therefore, geoengineering knowledge and technology retain their leadership roles in any upcoming radioactive waste management decisions for the sustainable development of nuclear energy.

Acknowledgements

This work was supported by the Nuclear Research & Development Program of the Korea Science and Engineering Foundation (KOSEF) through a grant funded by the Korean government (MEST) (Grant code: M20703040004-08M0304-00410). The authors would like to acknowledge ENRESA for funding the work presented in Section 4. This experimental and numerical work was also funded by the European Commission through the FEBEX I, FEBEX II and NF-PRO projects. The authors are also grateful to Drs. Gens, Olivella and Guimaraes for their comments involvement in the development of the numerical tools presented in this work.

References

Alexander, W. R. and Mckinley, L. E. (2007). *Deep geological disposal of radioactive waste*, Radioactivity in the Environment Vol. 9, Elsevier, Oxford.

Alonso, E., Gens, A., and Josa, A. (1990). “A constitutive model for partially saturated soils.” *Géotechnique,* Vol. 40, No. 3, pp. 405-430.

Andersson, C. G., Emilsson, G., Eriksson, P., and Westman, M. (2004). *Status report, canister fabrication*, SKB TR-04-23, Swedish Nuclear Fuel and Waste Manangement Co., Stockholm.

Autio, J. and Kirkkomäki, T. (1996). *Boring of full scale demonstration holes using a novel dry blind boring method*, SKB TR-96-21, Swedish Nuclear Fuel and Waste Manangement Co., Stockholm.

Bäckblom, G. and Lindgren, E. (2005). *KBS-3H-Excavation of two horizontal drifts at the Äspö Hard Rock Laboratory during year 2004-2005*, SKB R-05-44, Swedish Nuclear Fuel and Waste Manangement Co., Stockholm.

Bastiaens, W., Bernier, F., and Li, X. L. (2007). “SELFRAC: Experiments and conclusions on fracturing, self-healing and self-sealing processes in clays.” *Physics and Chemistry of the Earth*, Vol. 32, Nos. 8-14, pp. 600-615.

Bernier, F., Li, X. L., Bastiaens, W., Ortiz, L., Van Geet M., Wouters, L., Frieg, B., Blümling, P., Desrues, J., Viaggiani, G. Coll, C., Chanchole, S., De Greef, V., Hamza, R., Malinsky, L., Vervoort, A., Vanbrabant, Y., Debecker, B., Verstraelen, J., Govaerts, A., Wevers, M., Labiouse, V., Escoffier, S., Mathier, J. F., Gastaldo, L., Bühler, (2007). *Fractures and self-healing within the excavation disturbed zone in clays (SELFRAC)*, SELFRAC Project Final Report, European Commission.

Bodansky, D. (2004). *Nuclear energy: Principles, practices and prospects*, 2nd Ed., American Institute of Physics, New York.

Bodén, A. and Sievänen, U. (2006). *Low-pH injection grout for deep repositories*. Posiva WR-2005-24, Posiva Oy., Olkiluoto.

Bühler, C., (2005). *SELFRAC (SE) Experiment – Long-term dilatometer experiment*, Mont Terri Project, Technical Report, TN 2003-17, Mont Terri Rock Laboratory.

CODE_BRIGHT User’s Manual (2010). Technical University of Catalonia.

Collin, F., Li, X., Radu, J. P., and Charlier, R. (2002). “Thermo-hydro-mechanical coupling in clay barriers.” *Engineering Geology*, Vol. 64, Nos. 2-3, pp. 179-193.

Davies, C. and Bernier, F. (2005). “Impact of the excavation disturbed or damaged zone (EDZ) on the performance of radioactive waste geological repositories.” *Proc. of the Eurpean Commission Cluster Conference and Workshop*, Luxembourg.

Dixon, D., Chandler, N., Graham, J., and Gray, M. (2002). “Two large-scale sealing tests conducted at Atomic Energy of Canada’s underground research laboratory: The buffer-container experiment and the isothermal test.” *Can. Geotech. Jnl*., Vol. 39, No. 3, pp. 503-518.

European Commission (2004). *Geological disposal of radioactive wastes produced by nuclear power: From concept to implementation,* European Commission, Belgium.

Falck, W. E. and Nilsson, K. F. (2009). *Geological disposal of radioactive waste: Moving towards implementation*, JRC Reference Report, JRC European Commission, Washington, D.C.

Fernandez, L., Alonso, M. C., Garcia, J. L., and Hidalgo, A. (2005). “Shotcrete development for low-pH cements.” ESDRED, *Proc. of the 2nd Low-pH workshop*, Madrid, June 15-16, pp. 161-171.

Gallé, C. (1998). “Migration des gaz et pression de rupture dans une argile compactée destinée á la barriére ouvragée d’un stockage profond.” *Bull. Soc. Géol*., Vol. 169, No. 5, pp. 675-680.

Gallé, C. (2000). “Gas breakthrough pressure in compacted Fo-Ca clay and interfacial gas overpressure in waste disposal context.” *Applied Clay Science*, Vol. 17, Nos. 1-2, pp. 85-97.

Gawin, D., Baggio, P., and Schrefler, B. A. (1995). “Coupled heat, water and gas flow in deformable porous media.” *Int. J. Numer. Meth. Fluids*, Vol. 20, Nos. 8-9, pp. 969-987.

Gens, A. and Alonso, E. E. (1992). “A framework for the behaviour of unsaturated expansive clays.” *Can. Geotech. Jnl*.,Vol. 29, No. 6, pp. 1013-1032.

Gens, A., Sánchez, M., Guimarães, L., Alonso, E., Lloret, A., Olivella, S., Villar, M. V., and Huertas, F. (2009). “A full scale in situ heating test for high level nuclear waste disposal: Observations, analysis and interpretation.” *Géotechnique*, Vol. 59, No. 4, pp. 377-399.

Graham, J., Halayko, K. G., Hume, H., Kirkham, T., Gray, M., and Oscarson, D. (2002). “A capillarity-advective model for gas break-through in clays.” *Engineering Geology*, Vol. 64, Nos. 2-3, pp. 273-

286.

Guimarães, L. Do N., Gens, A., and Olivella, S. (1999). “THM and reactive transport coupling in unsaturated porous media.” *Proc. 7th Int. Symp. on Numerical Models in Geomechanics, Graz*, pp. 303-308.

Guimarães, L. Do N., Gens, A., and Olivella, S. (2007). “Coupled thermo-hydro-mechanical and chemical analysis of expansive clay subjected to heating and hydration.” *Transp. in Porous Media*, Vol. 66, No. 3, pp. 341-372.

Guimarães, L., Gens, A., Sánchez, M., and Olivella, S. (2009). “Coupled THMC modelling of unsaturated swelling clays: Constitutive formulation and boundary value problems.” *Proc. of 4th Asian Pacific Conference on Unsaturated Soils*, Newcastle, Australia, pp. 515-529.

Harrington, J. F. and Horseman, S. T. (2003). *Gas migration in KBS-3 buffer bentonite: Sensitivity of test parameters to experimental boundary conditions*, SKB TR-03-02, Swedish Nuclear Fuel and Waste Manangement Co., Stockholm.

Heitz, D., Trick, T., and Bühler, C. (2003). *SELFRAC (SE) experiment – Long-term plate load experiment*, Mont Terri Project, Technical Report, TN 2003-51, Mont Terri Rock Laboratory.

Hoch, A. R., Cliffe, K. A., Swift, B. T., and Rodwell, W. R. (2004). *Modelling gas migration in compacted bentonite: GAMBIT club phase 3 final report*, POSIVA 2004-02, Posiva Oy., Olkiluoto.

Horseman, S. T. and Harrington, J. F. (1997). *Study of gas migration in Mx80 buffer bentonite*, BGS International Report WE/97/7, SKB.

Horseman, S. T., Harrington, J. F., and Sellin, P. (1997). “Gas migration in Mx80 buffer bentonite.” *Proceedings of the Scientific Basis for Nuclear Waste Management XX*, Eds. W.J. Gray and I.R. Triay, Materials Research Society.

Hudson, J. A., Bäckström, A., Rutqvist, J., Jing, L., Backers, T., Chijimatsu, M., Christiansson, R., Feng, X. T., Kobayashi, A., Koyama, T., Lee, H. S., Neretnieks, I., Pan, P. Z., Rinne, M., and Shen, B. T. (2009). “Characterising and modelling the excavation damaged zone in crystalline rock in the context of radioactive waste disposal.” *Environmental Geolology*, Vol. 57, No. 6, pp. 1275-1297.

Huertas, F., Farina, P., Farias, J., Garcýa-Sineriz, J. L., Villar, M. V., Fernandez, A. M., Martýn, P. L., Elorza, F. J., Gens, A., Sanchez, M., Lloret, A., Samper, J., and Martýnez, M. A. (2006). *Full-scale engineered barrier experiment*, Updated Final Report, Technical Publication 05-0/2006. Madrid: Enresa.

Hume, H. B. (1999). *Gas breakthrough in compacted Avolnea bentonite*, MSc Thesis, University of Manitoba, Canada.

IAEA (1993). *Report on radioactive waste disposal details*, Technical Reports Series No. 349, IAEA, Vienna.

IAEA (1997). *Characterization of radioactive waste forms and packages*, Technical Reports Series No. 383, IAEA, Vienna.

IAEA (2003a). *Scientific and technical basis for the geological disposal of radioactive wastes*, Technical Reports Series No. 413, IAEA, Vienna.

IAEA (2003b). *Effects of radiation and environmental factors on the durability of materials in spent fuel storage and disposal*, IAEA-TECDOC-1316, IAEA, Vienna.

IAEA (2006). *Geological disposal of radioactive waste safety requirements*, Safety Standards Series No. WS-R-4, IAEA, Vienna.

IAEA (2010). *Nuclear technology review 2010*, IAEA, Vienna.

JNC (2000). *H12 : Project to establish the scientific and technical basis for HLW disposal in Japan-project overview report*, JNC TN1410 200-001, Japan Nuclear Cycle Development Institute, Ibaraki.

Kronlöf, A. (2005). *Injection grout for deep repositories-low pH cementitious grout for larger fractures: Testing effect of superplasticizer on technical performance*, Posiva WR-2005-08, Posiva Oy., Olkiluoto.

Martin, P. L. and Barcala, J. M. (2005). “Large scale buffer material test: Mock-up experiment at CIEMAT.” *Engineering Geology*, Vol. 81, No. 3, pp. 298-316.

NAGRA (2002). *Technical-scientific contributions on the topic of nuclear waste management*, NAGRA Bulletin 34, Switzerland.

NAS (1957). *The disposal of radioactive waste on land*, National Academy of Sciences, NAS Washington, D.C.

National Academies (2006). *Geological and geotechnical engineering in the new millennium : Opportunites for research and technological innovation*, The National Academies Press, Washington, D.C.

Nuclear Energy Agency (1999). *Geological disposal of radioactive waste : Review of developments in the last decade*, OECE Nuclear Energy Agency, Paris.

OECD-Nuclear Energy Agency (2003). *Engineered barrier systems and the safety of deep geological repositories*, Sate-of-the-art Report, OECD-NEA, Paris.

OECD Nuclear Energy Agency (2008). *Nuclear energy outlook 2008*, NEA, France.

Olivella, S., Carrera, J., Gens, A., and Alonso, E. E. (1994). “Non-isothermal multiphase flow of brine and gas through saline media.” *Transport in Porous Media*, Vol. 15, pp. 271-293.

Olivella, S., Gens, A., Carrera, J., and Alonso, E. E. (1996). “Numerical formulation for a simulator (CODE-BRIGHT) for the coupled analysis of saline media.” *Engineering Computations*, Vol. 13, No. 7, pp. 87-112.

Orantie, K. and Kuosa, H. (2007). *Durability 2007 injection grout investigation-Background description*, Posiva WR-2008-54, Posiva Oy., Olkiluoto.

Pusch, R. and Forsberg, T. (1983). *Gas migration through bentonite clay*, SKBF/KBS TR-83-71, Swedish Nuclear Fuel and Waste Manangement Co., Stockholm.

Pusch, R., Ranhagen, L., and Nilsson, K. (1985). *Gas migration through Mx-80 bentonite*, Nagra Technical Report 85-36, Switzerland.

Rutqvist, J., Barr, D., Datta, R., Gens, A., Millard, M., Olivella, S., Tsang, C. F., and Tsang, Y. (2005). “Coupled thermal-hydrological-mechanical analysis of the Yucca Mountain Drift Scale Test - comparison of field results to predictions of four different models.” *Int. J. Rock Mech. & Min. Sci.*, Vol. 42, No. 5-6, pp. 680-697.

Sánchez, M., Gens, A., Guimarães, L., and Olivella S. (2010). “THM analysis of a large scale heating test incorporating material fabric changes.” *Int. Jnl. Numer. Anal. Meth. Geomech, (*Accepted).

Sánchez, M., Gens, A., Guimarães, L., and Olivella, S. (2005). “A double structure generalized plasticity model for expansive materials.” *Int. Jnl. Numer. Anal. Meth. Geomech*, Vol. 29, No. 8, pp. 751-787.

Sánchez, M., Gens, A., Guimarães, L., and Olivella, S. (2008). “Implementation algorithm of a generalized plasticity model for swelling clays.” *Computers and Geotechnics*, Vol. 35, No. 6, pp. 860-871.

Sievänen, U., Raivio, P., Vuorinen, U., Hansen, J., Norokallio, J., and Syrjänen, P. (2006). *Optimization of technical properties of low-pH cementitious injection grout: Laboratory tests and pilot field test 3*. Posiva WR-2006-85, Posiva Oy., Olkiluoto.

Svemar, C. and Push, R. (2002). *Äspö hard rock laboratory*, International Progress Report, IPR-00-30. SKB, Stockholm.

Swedish Nuclear Fuel and Waste Manangement Co.SKB (2004). *RD&D-programme 2004*, SKB TR-04-21, SKBSwedish Nuclear

Fuel and Waste Manangement Co., Stockholm.

Swedish Nuclear Fuel and Waste Manangement Co.SKB (2007). *RD&D-programme 2007*, SKB TR-07-12, SKBSwedish Nuclear Fuel and Waste Manangement Co., Stockholm.

Tanai, K., Kanno, T., and Gallé, C. (1997). “Experimental study of gas permeabilities and breakthrough pressures in clays.” *Proc. of the Scientific Basis of Nuclear Waste Management Conference Number XX*, Material Research Society, Boston, USA.

Thomas, H. R. and Cleall, P. J. (1998). “Coupled thermo hydraulic mechanical behaviour of unsaturated soil, including expansive clays.” *Workshop on Microstructural Modelling of Natural and Artificially Prepared Clay Soils with Special Emphasis on the Use of Clays for Waste Isolation*, (R. Pusch, Ed.), Lund, Sweden, pp. 86-93.

Thomas, H. R. and He, Y. (1995). “An analysis of coupled heat, moisture and air transfer in a deformable unsaturated soil.” *Geotechnique*, Vol. 45, No. 4, pp. 677-689.

Thomas, H. R., Cleall. P. J., and Hashm, A. A. (2001). “Thermal/Hydraulic/Chemical/Mechanical (THCM) behavior of partly saturated soil.” *Computer Methods and Advances in Geomechanics* (Desai *et al*., Eds), A.A. Balkema, Rotterdam, Vol. 1, pp. 756-763.

Torbjörn, H. P., Björn, L., and Carsten, V. (2005). “Selective stabilization of deep core drilled boreholes using low-pH cement.” *Proc. 2nd Low-pH Workshop*, ESDRED, Madrid, Spain, pp. 122-137.

Tsang, C. F., Bernier, F., and Davies, C. (2005). “Geohydromechanical processes in the excavation damaged zone in crystalline rock, rock salt, and indurated and plastic calys-in the context of radioactive waste disposal.” *Int. J. Rock Mech. Min. Sci*., Vol. 42, No. 1, pp. 109-125.

Volckaert, G., Dereeper, B., Put, M., Ortiz, L., Gens, A., Vaunat, J., Villar, M. V., Martin, P. L., Imbert, C., Lassabatère, T., Mouche, E., and Cany, F. (2000). *A Large-scale in situ demonstration test for repository sealing in an Argillaceous Host Rock*, Reseal Phase I Project Report, European Commission, Brussels.

WNA (2009). *Radioactive waste management* (http://www.world-nuclear.org/info/inf04.html).