Engineering Challenges in the Geological Disposal of Radioactive Waste and Carbon Dioxide

Jean-Pierre Tshibangu K. and Fanny Descamps

Abstract This chapter deals with engineering issues related to the geological disposal of radioactive waste and carbon dioxide. An overview of the methodology for tackling these challenges is given, starting from the understanding of the geological context and the rock characterization (in laboratory and in situ) to the design and construction of the repository. We recall first the fundamentals of porous media and the transport mechanisms of solutes and gas in geological formations. Then we describe the various steps in the engineering design of underground workings, from site investigation to long-term safety and performance assessment. The particular cases of radioactive waste and carbon dioxide disposal are developed independently. Finally, we compare both types of disposal from the engineering point of view and show that, even if obvious differences exist, some requirements are similar. It is therefore valuable to develop a comparative view of the two approaches in order to benefit from the experience acquired.

Keywords Natural barrier • Engineered barrier system • Transport in porous medium • Long-term sealing • Geological disposal

1 Introduction

The main engineering challenge involved in storing waste materials in geological formations is to develop technologies that are safe enough to protect public health and avoid pollution or contamination of potential future resources (potable water, energy resources). Disposal should then be designed so as to limit the migration of pollutants from the geological formations.

J-P Tshibangu K. (✉) and F. Descamps
Mining Engineering Department, University of Mons, rue du Joncquois 53, 7000 Mons, Belgium
e-mail: jean-pierre.tshibangu@umons.ac.be; fanny.descamps@umons.ac.be

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The first step in addressing geological storage is to find geological formations with secure holes (or voids) to host the waste material. The hole concept can be understood either on a small scale, in terms of pores or cracks to allow the displacement of fluid waste, or on a bigger scale, in terms of cavities (natural or man-made). By secure, we mean that the voided zone should be surrounded by a barrier that is able to considerably slow down the migration of any pollutant beyond the boundaries of the targeted disposal reservoir.

Every geological formation has its own distinctive physical properties, and all will allow chemical transfer to a certain extent. Thus, after identification of formations that are able to host waste materials, a second step would be to perform laboratory and field tests to characterize the rock materials that make up the formation.

In a third step, the engineers must design the requisite technology to allow the disposal site to be accessed and the waste to be stored securely. In fact, construction techniques must be designed in such a way that secure openings can be built that permit no or very limited leakage over time. Depending on the depth and size of a future repository, the techniques will be developed using the approaches used in the mining or petroleum industries. In general, a radioactive waste (RW) repository would be dealt with in accordance with mining technologies and carbon dioxide (CO_2) disposal in accordance with deep-wellbore petroleum technologies.

To assess the performance of a RW repository on a very long-term basis, Gomit et al. (1997) carried out an extensive study in the framework of the EVEREST project, funded by the European Union. The study described and evaluated the impact of events that can affect the quality of the repository: phenomena of natural origin (variation of Earth orbital parameters, tectonics, diapirism and meteorite impact) and phenomena of human origin (non-detected features, sealing defects, inadvertent human intrusion, human-induced climate change, voluntary human intrusion and war). Comparable approaches are being developed, though in a less detailed manner, to address long-term security issues for CO_2 disposal. These combine mechanisms of structural and stratigraphic, residual, solubility, and mineral trapping (Benson et al. 2005).

2 Theoretical Issues Related to Fluid Solutes and Gas Transport in Geological Formations

2.1 The Porous Medium

Every geological formation can be considered to a certain degree as a porous medium and can therefore exhibit two essential characteristics: capacity for storage and transmissibility of fluids.

A porous medium contains voids or spaces that form the porosity. Two types of porosity can be distinguished: *primary or matrix porosity*, which generally refers to void spaces in sedimentary rocks that remain after sedimentation and compaction,

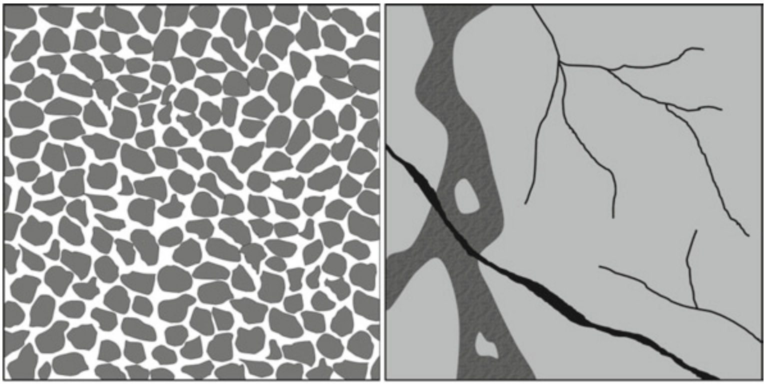


Fig. 1 Primary (matrix) and secondary (fractures) porosities

and *secondary porosity* which is due to fractures and other discontinuities in the material (Fig. 1). Because of past tectonic activities, most sedimentary rock formations exhibit both primary and secondary porosity.

Porosity (ϕ) is defined as a percentage or fraction of the void space with respect to the bulk volume of the rock. It is expressed as a percentage by:

$$\phi = \frac{V_v}{V} \cdot 100 \quad (1)$$

where V_v is the volume of voids and V the total volume.

If the porous medium is saturated by a fluid, usually only part of this fluid will flow through the medium. An effective porosity, ϕ_e, also known as the capacity to permit free flow, can then be defined by:

$$\phi_e = \frac{Volume\ free\ fluid}{Total\ volume} < \phi \quad (2)$$

ϕ_e depends on both the porosity and the grain fineness; the smaller the grain size, the smaller this quantity. For clays, effective porosity is very small compared with total porosity, whereas in sandstones, these two properties are very close in size.

When the porous medium contains more than one fluid, the saturation concept has to be defined. This is the case, for instance, when the pores contain a liquid phase, like water, and a gaseous one, like air.

Determination of porosity requires measurement of the total volume and either the pore volume or the matrix volume. The total volume of a rock sample can be measured by fluid displacement, while the pore volume can be measured according to different techniques, the most usual one being as follows: the rock sample is dried and weighed (W_d), and then saturated in brine (salt-saturated water) or another fluid, and then weighed again (W_{sat}). The connected porosity is then given by:

$$\phi = \left(\frac{W_{sat} - W_d}{\gamma_{fl} \cdot V_{sam}} \right) \cdot 100 \tag{3}$$

where γ_{fl} represents the unit weight of the injected fluid and V_{sam} is the volume of the sample.

2.2 Transport Mechanisms in Porous Media

Different mechanisms can be invoked to describe the transport of molecular species through porous media (Mody and Hale 1993; Horseman et al. 1996; Marivoet et al. 1997). Among them, we focus on the following two main mechanisms:

- *Hydraulic flow* or *advection*, the driving force of which is the hydraulic pressure difference and whose flow rate depends on the permeability of the porous medium;
- *Diffusion*, the driving force of which is the chemical potential or concentration difference of dissolved species contained in the pore fluid.

Other interesting mechanisms favouring the geological disposal of RW and/or CO_2 can be mentioned: retardation due to chemical sorption (reaction with minerals on the solid surface), dissolution into the formation fluid, mineralization, dispersion caused by formation heterogeneities, and buoyancy (due to the difference in density between the two fluids). Most of the mechanisms listed can be modelled mathematically using the same thermodynamics concepts presented in the subsections below (Marivoet et al. 1997; Benson et al. 2005).

2.2.1 Hydraulic Conductivity

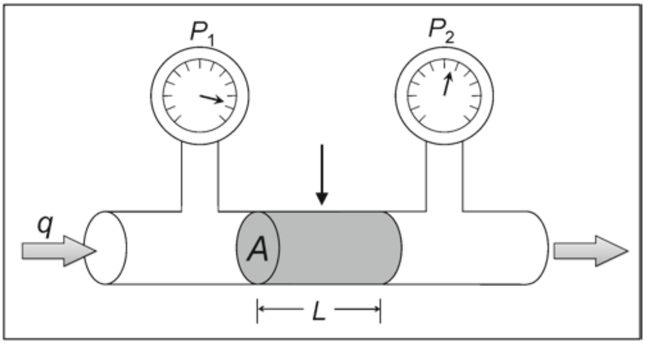
When choosing a coordinate system such that the z axis is oriented in the direction of gravity g (i.e. downwards), and neglecting the effect of velocity (because of the very low kinetic energy involved), a fluid particle (water in the present case) having an ordinate z and a pressure p will have a hydraulic charge (h) defined by:

$$h = \frac{p}{\gamma_w} - z \tag{4}$$

where γ_w is the water unit weight.

The hydraulic charge represents a quantity that is proportional to the internal energy of a particle of mass M, and this is the main driving force in the flow of fluids through porous media. For deep reservoirs (i.e. more than 1,000 m), the hydraulic charge is given mainly by the pressure term.

The magnitude of the hydraulic flow is characterized by the permeability of the medium. The permeability of a rock is a measure of a specific flow capacity and



P_1 and P_2	Inlet and outlet fluid pressures
A	Cross section of the sample
L	Length of the sample
q	Flow rate

Fig. 2 Permeability test principle

can be determined only by a flow experiment. As permeability depends upon continuity of pore space, there is no unique relation between the porosity of a rock and its permeability.

The permeability can be expressed by Darcy's law as:

$$\vec{q} = -k \nabla p \tag{5}$$

where $\vec{q}$ is the flow rate (m^3/s); k is the permeability (Darcy); p is the fluid pressure.

In this equation, the permeability depends on both the rock characteristics and the fluid viscosity. The two effects can be split and the parameter expressed independently with respect to the fluid.

Measurement of the permeability can be performed on a cylindrical sample by flushing it with water, gas (nitrogen or air) or another fluid, the viscosity of which is known. A differential pressure is applied on the two faces of the sample, and the flow rate is measured to assess the permeability (Fig. 2).

Multiphase Flow in Porous Media (Non-miscible Fluids in Saturated Media)

In oil reservoirs three different fluids can be displaced: water, oil and gas. The effective permeability for each fluid is derived from Darcy's law and is always lower than the overall true permeability of the medium, also known as absolute permeability (Dake 1978).

The *relative permeability* is defined as the ratio of effective permeability to absolute permeability. It depends on saturation and wettability (defined as the tendency of a fluid to displace another fluid from a solid surface). The relative permeability notion is very important when attempts are made to recover oil, for example by injecting CO_2.

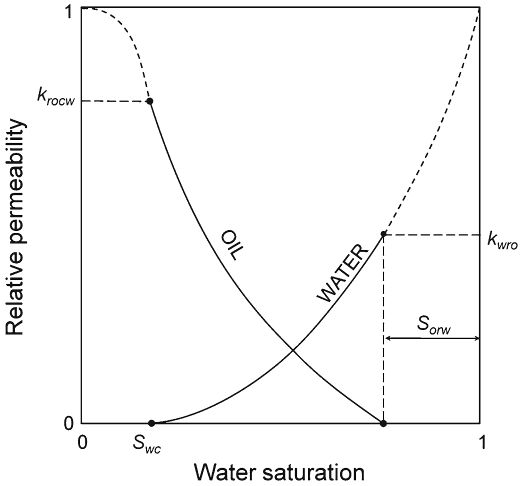


Fig. 3 Water–oil relative permeability curves in the case of oil recovery by water injection

Figure 3 shows the evolution of water–oil relative permeabilities versus water saturation. For a new petroleum reservoir (onset of production), the water saturation is minimum (S_{wc} is the connate or irreducible water saturation), and the relative permeability to oil is then maximum (k_{rocw}). In the course of production life, the water saturation increases, thereby increasing the relative permeability to water and, hence, decreasing the relative permeability to oil. It is known that when the reservoir is tending to depletion, it produces more water than oil. When the oil saturation decreases to S_{orw}, the residual saturation, there will be no more oil flow. When oil production is being enhanced by CO_2 injection and disposal, CO_2 will play the role of water, and the risk of recovering the gas to be stored from the production wells must be taken into account. Assessment must thus be made as accurately as possible of the instant at which CO_2 injection has to be stopped.

2.2.2 Fluid Diffusivity Law

To assess the movement of fluids in deformable solids, the mass conservation principle expressed by the continuity equation must be used. This relates the rate of flow of fluid into a small volume to the rate of increase of the amount of fluid in this volume (Jaeger and Cook 1979). Combining the continuity equation with the transport law (Darcy's law in this case) will lead to a diffusivity equation.

When working in great depth conditions, the movement of fluids will be mainly driven by pressure, and the permeability will depend on the deformation of the solid skeleton (Charlez 1991; Coussy 1991). In such conditions, if the fluid is assumed to be non-compressible, the diffusion equation can be derived as:

$$k\nabla^2 p = -\frac{1}{\rho_{fl}}\frac{\delta m}{\delta \mathrm{t}} \tag{6}$$

where m is the variation of the amount of fluid by unit volume, p the pore pressure, t the time and ρ_{fl} the density of the fluid.

The use of this equation, coupled to the mechanical behaviour of the medium, can lead to an assessment of the evolution of the reservoir and the fluid transfer (or leakage) over time.

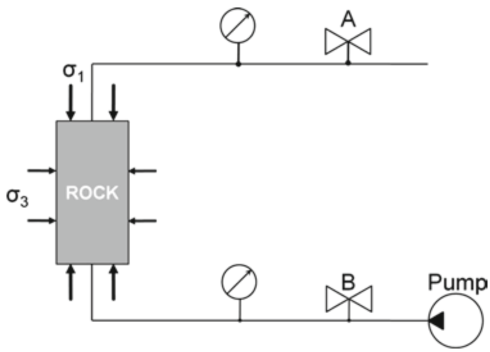
The diffusivity equation cannot be solved on its own because it contains two unknowns. When working in geomaterials, it has to be combined with constitutive laws like the thermo-poro-elasticity law to provide more equations. An example of state equations when the effect of temperature is neglected is given below:

$$[\sigma] = [\sigma_0] + \frac{E}{1+\nu}[\varepsilon] + \frac{E\nu}{(1+\nu)(1-2\nu)} tr[\varepsilon]\cdot[1] + b(p-p_0)\cdot[1] \tag{7}$$

$$p = p_0 + M\left(b \operatorname{tr}[\varepsilon] + \frac{m}{\rho_{fl\,0}}\right) \tag{8}$$

where $[\sigma]$ is the stress tensor (the subscript 0 is relative to the initial state of stresses); $[\varepsilon]$ is the strain tensor; [1] is the unit tensor; $\operatorname{tr}[\varepsilon] = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$ is the volumetric strain; m is the fluid mass increment; b and M are the Biot coefficient and modulus; p is the pore pressure (the subscript 0 relates to the initial pressure); E is the Young modulus; ν is the Poisson ratio; b, M, E and ν are known as the poro-elastic parameters of the porous medium.

The triaxial test with a pore pressure control is the most useful experimental system for determining the poro-elastic parameters. In fact, it is easy to measure the components of the strain tensor $[\varepsilon]$, which describes the deformation of the skeleton



The rock sample is submitted to mechanical stresses σ_1 and σ_3; σ_1 is the major principal stress (*thick arrows*) whereas σ_3 is the minor principal or confining stress (*thin arrows*). The pore fluid is injected by means of a pump. Two valves (*A and B*) allow drained or undrained experiments. Pressure sensors give the inlet and outlet pore pressure.

Fig. 4 Triaxial test principle with pore pressure control of the rock sample, to drive the components of the stress tensor [σ], and to a lesser extent the variation of the pore pressure ($p - p_0$). The sketch in Fig. 4 shows the principle of a triaxial test that enables both drained ($p = p_0$) and undrained ($m = 0$) experiments.

2.2.3 Generalization of the Transport Theory

When dealing with diffusion mechanisms, the transport equation can be generalized as follows (Sherwood 1993; Tshibangu et al. 1996):

$$q_i^r = -\sum_s L_{ij}^{rs} \nabla_j C^s \tag{9}$$

where q_i^r is the mass flux of the r-th ionic species in direction i; C^s is the concentration of species s; L_{ij}^{rs} is the diffusion coefficient of the ionic species r in the presence of species s with a concentration C^s.

The mass conservation of ionic species r can be written as:

$$\nabla \cdot q^r = -\frac{\partial m^r}{\partial \mathrm{t}} \tag{10}$$

Combining this continuity equation with the transport law (9) will give the classical diffusion equation. When considering a one-dimensional problem (direction x) in which only the own concentration gradient of species r is taken into account (Put and Henrion 1988), the following simplified diffusion equation can be derived:

$$\frac{\partial^2 C^r}{\partial x^2} = \frac{1}{L^r} \frac{\partial C^r}{\partial \mathrm{t}} \tag{11}$$

L^r is the apparent diffusion coefficient for the ionic species considered. It depends on the specific conditions of the experiments. Put and Henrion (1988) define such a coefficient as being dependent on the diffusion coefficient in the liquid and the retardation factor to be applied to radionuclide diffusion mechanisms.

If a relationship can be established between the concentration and the mechanical behaviour of the solid skeleton, then the generalized poro-elasticity law can be written as:

$$d\varepsilon_{ij} = S_{ijkl} d\sigma_{kl} + \sum_r Q_{ij}^r \, d\mu^r \tag{12}$$

$$dm^r = Q_{ij}^r d\sigma_{ij} + \sum_s B^{rs} d\mu^s \tag{13}$$

where μ^r is the chemical potential of species r; m^r is the mass of species r per unit volume; ε_{ij} is the strain (or deformation) tensor; σ_{ij} is the stress tensor; S_{ijkl} is the matrix containing elastic properties (Young's modulus, Poisson's ratio, shearing modulus, etc.); Q_{ij}^r and B^{rs} are parameters to be determined by specific experiments in which the strains of the solid or mass of a given species can be measured with respect to variation of the chemical potential.

Prior to designing the geological disposal, a preliminary study of the transport mechanisms of solutes and gas in the porous media will be critical to the choice of potential sites. In fact, as stated in Sect. 3, collecting rock samples from the field and performing typical experiments will allow the identification of the most relevant transport mechanisms and assessment of the physical parameters needed. The RW repository study, on the one hand, will need a good knowledge of the natural barrier constituted by the host formation: porosity, permeability, and thermo-hydro-mechanical parameters (i.e. the poro-elastic parameters described in Eqs. 12 and 13). The repository study of CO_2, on the other hand, will address not only the issue of the barrier concept (caprock formation), but also deal with the injection capacity in the potential reservoir (mainly driven by the pressure gradient). When CO_2 is stored in coal formations, for example, Darcy's law can be used to assess the volume to be injected and the generalized poro-elastic equations to deal with matrix deformation (swelling) due to the adsorption phenomenon that is driving the volume to be stored.

When a sufficient amount of data is collected from field and laboratory, databases and 3-D geological models can be built to enable the design of suitable techniques for underground disposal.

3 Designing and Building Underground Openings

According to Bieniawski (1992), engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation. Central to the process are the essential and complementary roles of analysis and synthesis. In addition, sociological, economic, aesthetic, legal and ethical considerations need to be included in the design process.

The engineering work to design and build underground facilities can be summarized in the following main steps:

- Site investigation;
- Laboratory characterization;
- Rock mass characterization;
- In situ and field tests;
- Modelling the behaviour of the planned underground openings;

- Construction;
- Monitoring during construction and use;
- Operation;
- Closure and post-closure monitoring;
- Long-term safety analyses and performance assessment.

3.1 Site Investigation and Laboratory Characterization

Depending on the geological information available, this step can start with field visual observations. Geological maps must first be consulted. In a further approach, geophysical studies can be undertaken to ascertain the geometry of geological formations underground, and samples can be collected for laboratory tests (Brown 1981). The most common sampling method is to drill to collect cores (coring) or cuttings (destructive drill bits) of rocks.

The samples collected can be submitted to various tests depending on the intended use of the future underground opening: petrographic analysis, physical properties (porosity, permeability, density), mechanical properties such as, for instance, the poro-elastic properties described in Sect. 2 (Young's modulus, Poisson's ratio, shearing modulus, bulk compressibility modulus, Biot's coefficient and modulus, etc.), and the rock failure mechanisms with the associated parameters (cohesion, friction angle, pore collapse strength, etc.).

3.2 Rock Mass Characterization

The physical parameters measured in the laboratory should be scaled up so that they are applicable to a large volume of rock in accordance with the size of the structure to be developed. Structural analysis, assessment of the quality of the rock mass, and evaluation of the mechanical properties of the rock mass all need to be performed.

The structural analysis is intended to identify discontinuities in terms of type (fault, fracture, joints, bedding planes), orientation (dip and direction), frequency, quality of filling materials (rough surfaces in contact or joints filled with soft gouge materials), and presence of water.

To qualify the rock mass, different indices have been developed like the Rock Quality Designation (RQD) (Deere 1963), Rock Mass Rating (RMR) (Bieniawski 1984), the Geological Strength Index (GSI) (Hoek and Brown 1998) and Barton's Q-index (Barton et al. 1977). These indices use structural data collected from cores or outcrops and combine with some typical rock strength parameters like the unconfined compressive strength (UCS) to give a numerical value of the quality of the rock mass. The RMR method, for instance, uses five parameters (the UCS, the

RQD, the spacing of the joints, the nature of the joints, and the water inflows/seepage) to all of which a score is attributed. By adding the five scores a characterization of the quality of the rock mass can be reached; this amount can be corrected to take into account the direction of fractures with respect to the orientation of the future opening (i.e. a tunnel).

The quality indices can also be used to assess the mechanical properties of a rock mass: strength, deformability and risk of failure. For instance, the Hoek-Brown failure criterion given in Eq. 14 is intended to assess the strength of a rock mass based on the assessed GSI index:

$$\sigma_1 = \sigma_3 + \sigma_{ci}\left(m_b \frac{\sigma_3}{\sigma_{ci}} + s\right)^a \tag{14}$$

where σ_1, σ_3 are the major and minor principal stresses; σ_{ci} is the unconfined strength of an intact rock sample; m_b is the Hoek-Brown constant for the rock mass; s and a are constants depending on the rock mass quality ($s=0$ for an aggregate and 1 for laboratory tests on intact rock samples).

The quality indices will be assessed more efficiently if databases are built that can be manipulated by numerical modelling software codes to allow 3-D geological models to be built. Modern mining or petroleum reservoir codes enable data from different sources to be used: cores, outcrops, faces of workings, results of mechanical tests, etc. Figure 5 gives an example of the description of a cored well and a geological model that can be built with data collected from many boreholes.

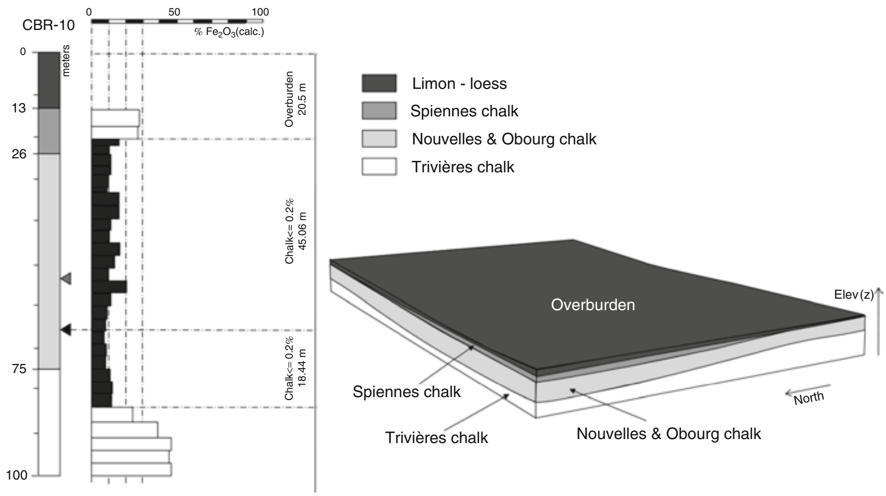


Fig. 5 A description of a cored well in terms of chemical composition and a simple geological model built with data from cores and essays.

3.3 From Modelling to Construction and Monitoring

After the collection of physical and geomechanical data and the building of geological models, the shape and size of specific underground structures or openings need to be designed, depending on what objectives are being pursued. If underground cavities are to be created for disposal purposes, then such cavities will be expected to remain open for the whole life of the operations. To predict the stability of underground openings, analytical and/or numerical modelling are used.

Underground openings can be of various shapes and types, and can be isolated or close to each other; thus a stress disturbance in a point of the rock mass situated in the neighbourhood of two openings can have effects that are superposed. Engineering practice distinguishes the following underground workings:

- Mining galleries and tunnels;
- Mining shafts;
- Mining working faces (areas in which the ore is being mined out);
- Wells for fluid extraction and/or injection;
- Large underground spaces (for example, space for a primary crusher in the mine, artificial cavities for storage of hydrocarbons, etc.).

The cross section of these openings can be circular, elliptical, rectangular, etc.

When dealing with the stability of underground openings, the equilibrium of a given opening has to be assessed over time. The equilibrium of solid bodies is governed by equilibrium equations obtained by balancing the forces acting on an infinitesimal element of the body (Jaeger and Cook 1979).

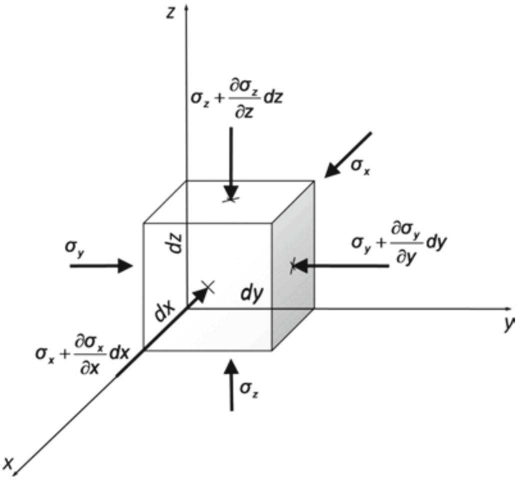
When considering a rectangular coordinate system *Oxyz*, an infinitesimal element can be represented as shown in Fig. 6. The six faces of the element are submitted to normal (σ_i) and tangential stresses (τ_{ij}), with subscripts being related to directions x, y and z. Figure 6 also describes the variation of stresses in the element for a given axis; this is expressed in terms of partial derivatives. Finally, the equilibrium equations are expressed as partial derivative equations, which are the most commonly used type in engineering problems:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho X = 0 \tag{15}$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho Y = 0 \tag{16}$$

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} + \rho Z = 0 \tag{17}$$

where ρ is the density; X, Y and Z are the components of body forces per unit volume (in this case, we will consider only gravity forces); σ_x, σ_y and σ_z are the normal stresses acting on sides perpendicular to axis x, y and z respectively; τ_{xy}, τ_{xz} and τ_{yz} are the tangential stresses.



Only normal stresses are shown to ensure legibility. The arrows represent the normal stresses on each face of the cube. For instance, in the x-direction, the normal stress is σ_x for x = 0.

Fig. 6 Equilibrium of an infinitesimal element (dx, dy, dz) in a Cartesian coordinate system

These are three equations with six unknowns (three components of normal stresses and three components of tangential stresses).

By assuming different behaviour laws for the material composing the rock mass, as described in Sect. 2, the stresses can be expressed in terms of the strains and the equilibrium equations then written in terms of strain or displacements.

Equilibrium equations have to be satisfied over the entire body under consideration, and also on the boundaries. In the latter case, the stresses have to balance the external forces applied to the body. This condition can be expressed in two dimensions by:

$$\bar{X} = l\sigma_x + m\tau_{xy} \quad (18)$$

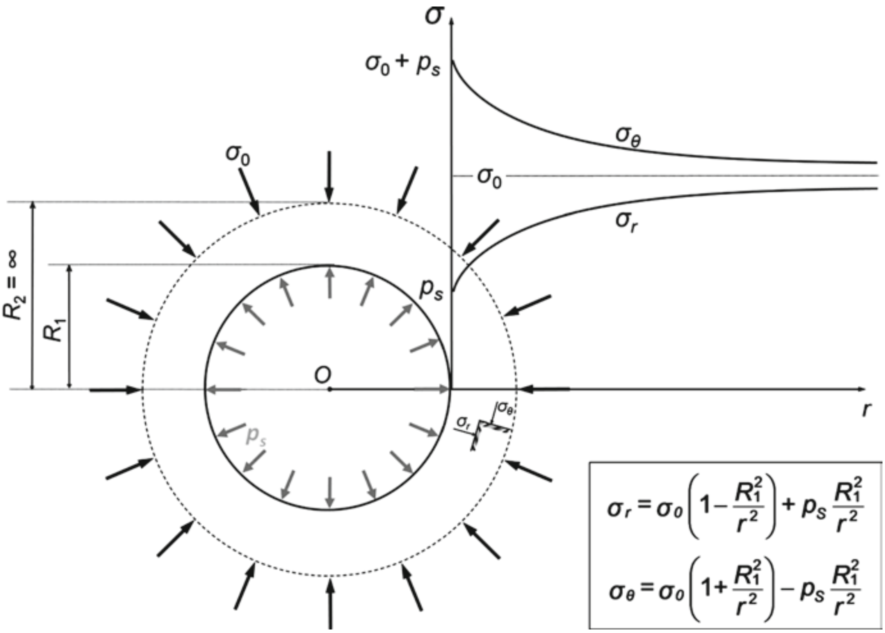
$$\bar{Y} = m\sigma_y + l\tau_{xy} \quad (19)$$

where $\bar{X}$ and $\bar{Y}$ are applied surface forces in directions x and y respectively; l and m are the direction parameters of the boundary linear element.

As stated earlier, a knowledge of equilibrium equations is inadequate for assessing the fields of stresses, strains, displacements, pore pressure, temperature and state of failure over the entire body and for modelling them. It is therefore necessary to look for additional equations (or constitutive laws) by setting typical assumptions on the behaviour of the geomaterial: elastic isotropic, poro-elastic, visco-elastic, perfectly plastic failure, etc. By combining the constitutive laws with equilibrium equations and boundary conditions, enough relationships are derived to solve the problem and an analytical or numerical approach can be used to assess the field variation of interesting variables. The so-called physical methods, which consist of building reduced-size models, have been used intensively in the past but are now of less importance because of the development of computers and numerical software codes.

The *analytical method* is used in homogeneous and isotropic media for simple geometrical shapes such as, for example, circular tunnels or galleries (Fig. 7). To a lesser extent, elliptical and rectangular openings can also be evaluated in this way. The general working method is built by combining equilibrium equations with elastic constitutive laws and typical boundary conditions. The final partial derivative system of equations (generally expressed in terms of displacements) is integrated, and integration constants are assessed using the boundary conditions. The solution is given in terms of simple formulae describing the variation of state variables (for example, stress, strain and displacement components) with respect to spatial coordinates and, sometimes, to time. Figure 7 gives an illustration of the variation of principal stresses (σ_θ and σ_r) in a polar coordinate system for a circular cavity with an isotropic natural stress σ_0 at infinity (Bouvart et al. 1988).

For *numerical methods*, different and widespread approaches exist: the finite element method (FEM), the boundary element method (BEM), the finite difference method (FDM) using Lagrangian elements, and the distinct element method (DEM). These methods allow more complex shapes of underground cavities that can be dug in complex geology environments to be studied. They generally consist



$$\sigma_r = \sigma_0\left(1-\frac{R_1^2}{r^2}\right) + p_s\frac{R_1^2}{r^2}$$

$$\sigma_\theta = \sigma_0\left(1+\frac{R_1^2}{r^2}\right) - p_s\frac{R_1^2}{r^2}$$

R_1 is the radius of the tunnel. σ_0 represents a lithostatic stress acting at an infinite radius R_2 whereas a supporting pressure p_s is applied on the wall. The evolution of the stresses versus the distance r from the tunnel centre shows a big difference between the radial stress σ_r and the tangential stress σ_0; for a so-called infinite distance the two stresses tend to reach the magnitude of the virgin rock stress σ_0.

Fig. 7 Example of a circular tunnel model in a homogeneous and isotropic medium of a subdivision of the studied model into different elements (meshing) with given shapes from which the unknown variables can be assessed. This is done by replacing the continuous function of the spatial variables (i.e. stresses, strains, displacements, etc.) by discrete approximations. This transforms continuous partial differential equations into discrete algebraic equations that can be solved by numerical computing methods. Figure 8 gives an example of a finite difference numerical model showing the distribution of pore pressure (a) and failed material or damaged (plastic) zone (b) for the bottom of the second shaft of the Mol research facility (Vereycken 2000). The technological development of computers during the last decades has brought a tremendous development in numerical computing methods. In fact, the software packages are designed so that big models can be run efficiently on personal computers.

Depending on the mechanical quality of the geological material, the excavation being designed can be self-supporting, or fail because of high induced stresses. To avoid the failure of underground openings, engineers need to design supporting structures and/or linings to ensure long-term stability. In the case of waste repositories, the structures also have to avoid or limit the leakage of the pollutants into aquifers. This means that supports need to be strong enough to balance the deformation of the rock mass and tight enough to limit the transfer of pollutants over the course of time. The mechanical characteristics of relevant supporting systems (concrete, steel arches, timber, etc.) can be used in numerical models to assess a new equilibrium of the excavation. To check the stability of the openings various failure criteria or strength envelopes that can be expressed in terms of stress functions then need to be assumed.

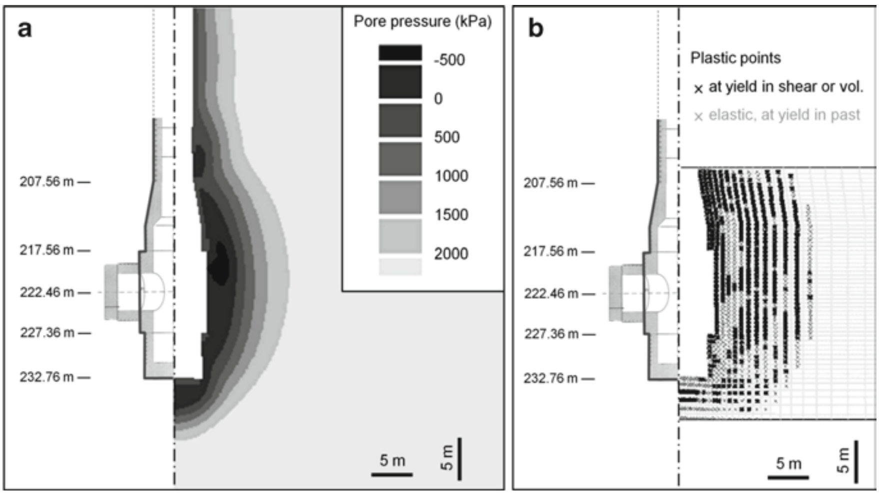


Fig. 8 Example of a finite difference numerical model showing the distribution of pore pressures (**a**) and failed material or damaged (plastic) zone (**b**) for the bottom of the second shaft of the Mol (Belgium) research facility (Vereycken 2000)

After construction, an underground opening has to be monitored, either visually or with the help of instruments. In engineering, structural monitoring may be carried out for different reasons, of which the two main ones are mentioned here (Brady and Brown 1999): (1) to ensure safety during construction and operation by giving warning of, for example, the development of excess ground deformations, groundwater pressures and loads in support elements; and (2) to check the validity of the assumptions, conceptual models and values of rock mass properties in design calculations. The monitoring measurements can be used to correct the mechanical parameters in the so-called back analysis.

Section 3 summarizes the working steps required to design, construct and use underground facilities. In the case of RW disposal, depending on the geomechanical properties of the targeted geological formation, the method described will be implemented with the objective of assessing the size, shape and support of cavities intended to receive the containers (canister or shroud). Combining geomechanical approaches with transport mechanisms (for instance, permeability will be modified in the plastic or damaged zone) will allow an evaluation of potential radionuclide migration in the rock mass and, hence, a sealing method to be designed accordingly. In the case of CO_2 disposal, the same working method can be applied to assess the stability of wells during both the drilling (calculation of the drilling fluid density) and the injection (calculation of casings and the production tubing) phases. The transport mechanisms will also be used to simulate the displacement of the injected gas in the reservoir and to check the sealing capacity of the caprock and the cemented well (see Branskill and Wilson 2011).

4 Disposing of Radioactive Waste in Underground Cavities

4.1 General Disposal Method

The waste material is deposited in a mine-like facility by moving the containers from the surface to underground. The disposal system must be based on the multi-barrier concept in which three subsystems can be considered (Marivoet et al. 1997): (1) the near field including the waste package, engineered barriers and the immediate part of the host rock that is significantly affected by the presence of the repository; (2) the far field (geosphere or natural barrier), including the host rock which surrounds the disposal system but which is not immediately affected by the presence of the cavity; and (3) the biosphere with the environment easily accessible by humans. This chapter focus mainly on the first two subsystems.

Storing RW, mainly high-level waste (HLW), will induce different phenomena in the near field, the physics of which has been invoked in Sects. 2 and 3 of this chapter: thermal processes, mechanical effects, chemical processes and radiological effects.

To fulfil the multi-barrier concept in both the near and far fields, selection of the geological host formation is critical. In Western Europe, three typical geological formations have been targeted.

- *Granite* (*France*): found in massive rock formations, but always fractured, so that the issue of permeability and leakage must be very carefully addressed;
- *Clay* (*Belgium, France*): generally impermeable and found in thick formations; but the thermal effects, especially in the near field must be addressed to avoid a thermo-hydro-mechanical coupling that could alter the isolation capability;
- *Salt* (*France, Germany, Netherlands*): found in massive impermeable geological formations.

Figure 9 shows an example of the design of the multi-barrier concept for the repository of HLW in the Boom Clay formation (ONDRAF/NIRAS 2001, 2008). The engineered barrier system (EBS) must prevent the release of radionuclides for as long as possible. The period of time for which the EBS is designed depends, in fact, on the disposal concept: in the Belgian case, the EBS is intended to prevent the release of radionuclides during the thermal phase (i.e. only a few thousand years) but in other concepts (e.g. Sweden), the EBS plays a more important role and on a longer timescale. In the current design, it consists of a supercontainer placed in a gallery lined with wedge blocks that is sealed by a cementitious backfill. The supercontainer comprises a carbon steel overpack and a Portland cement concrete buffer, with or without an outer stainless steel envelope. The overpack encloses the canisters of HLW or the spent fuel assemblies and is designed to contain and prevent the release of RW during the thermal phase.

Figure 10 gives the layout of a schematic repository. This is composed of a network of galleries connected to at least two entrances (i.e. shafts or declines)

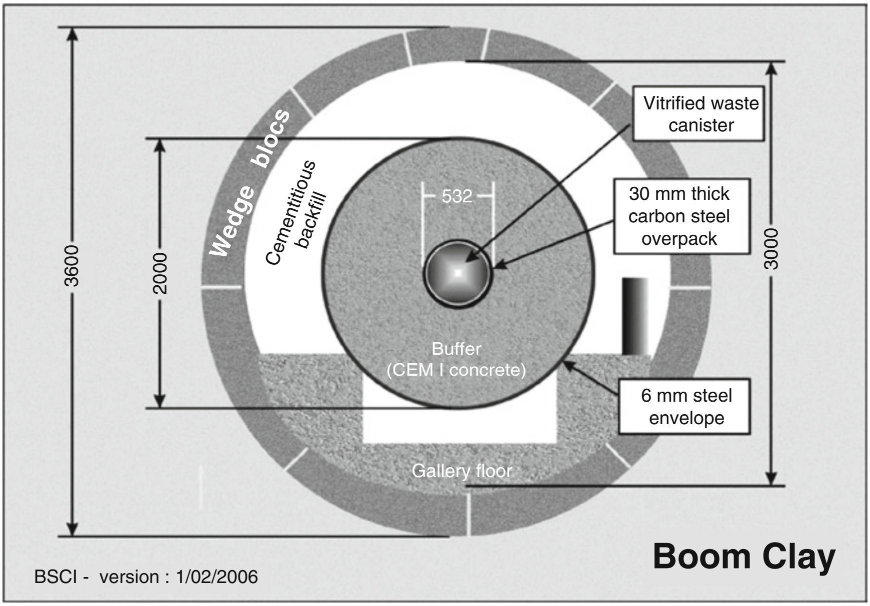
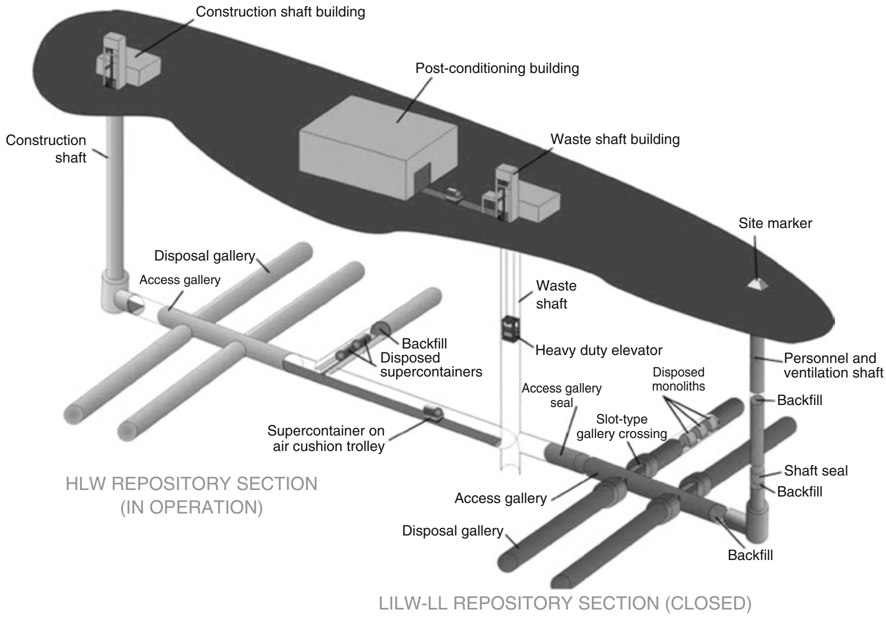


Fig. 9 The current reference concept for radioactive waste disposal in Belgium (© ONDRAF)



HLW: High-level waste
LILW-LL: Long-lived low- and intermediate-level waste

Fig. 10 Layout of the repository concept as it can be developed in the Boom Clay in Belgium (© ONDRAF)

to ensure ventilation of the underground facility and operational safety (personnel evacuation in case of emergency). HLW and intermediate-level waste (ILW) are stored in distinct areas. The dimension of the gallery will depend, among other things, on the diameter of the containers and the equipment used to handle them. All galleries and shafts will be backfilled in the closing phase of the repository.

4.2 Shaft Sinking and Gallery Digging

Accessing deep geological formations using mining methods can be performed in two ways:

- *By sinking a vertical or inclined shaft from the surface*: this structure needs to be a straight line and equipped with guides for the use of cages (elevators intended for men, equipment, and transport of broken rock material) or skips (buckets or containers used to handle broken rocks);
- *By digging a decline* (spirally inclined gallery) that can be used by road vehicles to access the deep galleries: conveyor belts can also be used to move broken rock material; the method is cheaper but is used mainly for shallow workings.

From the access structures (shaft or decline), near-horizontal galleries or rooms need to be developed to access the targeted areas. Pillars, whose dimensions can be assessed by mathematical modelling, are left between the galleries to ensure long-term stability. The digging method depends on the mechanical properties of the rock and the hydrological conditions:

- *Hard rocks–no water flow*: use of the classical drill and blast method or the mechanical method of tunnel boring machines (TBMs), but this latter method is cost-effective only for long tunnels;
- *Hard rocks–water flow*: use of cement grouting or other chemical to fill the cracks and faults before drilling and blasting; TBMs with compressed air or mud confinement;
- *Soft rocks–no water flow*: mechanical digging with use of open shield TBMs; the digging machine is a roadheader, back hoe, pneumatic or hydraulic hammer, etc.;
- *Soft rocks–water flow*: use of closed shield machines (TBMs generating confined space at the face with compressed air, mud pressure or mechanical support). The machine must be waterproof.

The drill and blast method in gallery digging is a cyclical method in which different operations follow each other in a repeating order. Each cycle should produce a certain length of excavated gallery or tunnel, a so-called round. The advance per round is usually 1–5 m depending on the characteristics of the rock mass. At a minimum, the following phases are included in a round:

- Drilling;
- Explosives charging;
- Blasting and ventilation;
- Scaling (removal of unstable rock pieces);
- Loading and hauling the blasted rock (mucking operations).

In addition to these, a supporting phase is normally needed, depending on the mechanical quality of the rock mass. This can comprise: rock bolting (use of steel rods), shotcreting (projection of concrete on the walls of the cavity), supporting arches and concrete lining.

A good knowledge of the ground conditions is required to estimate a schedule for a tunnelling project. Heavy immediate support, for instance, will lengthen the work cycle considerably. Figure 11 shows the typical operations included in a cycle of gallery digging.

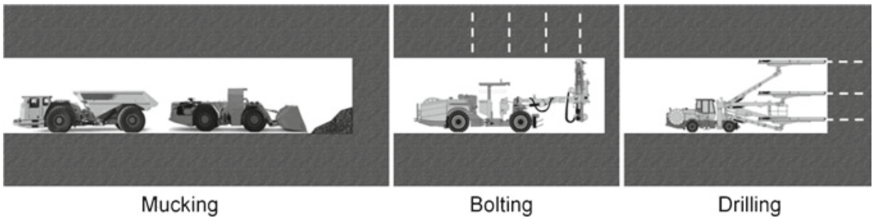


Fig. 11 The working cycle in the drill and blast method

Mechanized gallery digging can be performed either by continuous miners (road headers) or full face TBMs.

Continuous miners (also called road headers or point attack machines) are equipped with a rotating head with cutters or spikes to cut the rock. This type of machine is suitable for any cross sectional shape of the tunnel (circular, square, etc.). The technique is used only in soft to medium strength grounds. The abrasiveness of the rock is an important parameter in terms of addressing wear problems.

The *full face TBM* is composed of the boring machine itself followed by a trailer. The boring machine has a head (rotating or not) to cut circular tunnels by using cutting tools, the choice of which depends on the mechanical properties of the ground (strength, abrasiveness, water flow). The machine advances by use of gripping and pushing actuators. A mucking system is also included to remove the broken material from the face to the rear via a conveyor. The trailer carries all the technical equipment (compressor, support erecting systems, etc.).

Drilling and blasting are also cyclical operations in shaft sinking, as for horizontal openings. Drilling is performed by means of hand-operated pneumatic or hydraulic hammers. Sometimes the hammer can be secured on an upper platform and a mechanical pushing device can be used.

The mechanical shaft-sinking technique is used mainly for special working conditions like soft aquiferous ground. We indicate here two of various working methods: (1) the large- diameter boring machine system (up to 5–6 m) uses the drilling technique with the walls being supported during sinking by hydrostatic mud pressure; and (2) the pre-excavation ground freezing system. This second method uses a curtain of boreholes containing pipes in which brine refrigerated at −30°C is circulated.

5 Disposing of CO_2 by Injection from Deep Wellbores

5.1 General Disposal Method

Different mechanisms exist for storing CO_2 in geological formations (Benson et al. 2005): stratigraphic and structural physical trapping (below low permeability seals or caprocks), hydrodynamic physical trapping (fluids migrate very slowly over long distances, mainly in saline formations that do not have a closed trap), and geochemical trapping (solubility and mineralization).

One method for geological CO_2 storage is to drill wells and inject the gas in its supercritical state into permeable formations (reservoirs) situated at great depths (of at least 800–1,000 m to keep the CO_2 at the desired pressure). Different types of reservoirs can be used to meet the targeted conditions (Fig. 12): storing in depleted petroleum reservoirs, using the CO_2 pressure to improve the recovery of oil from producing fields (enhanced oil recovery or EOR); storing in deep saline aquifers; and storing in unmineable coal seams (with enhanced coalbed methane, or ECBM, production). Other possibilities like the use of abandoned mines or natural caverns

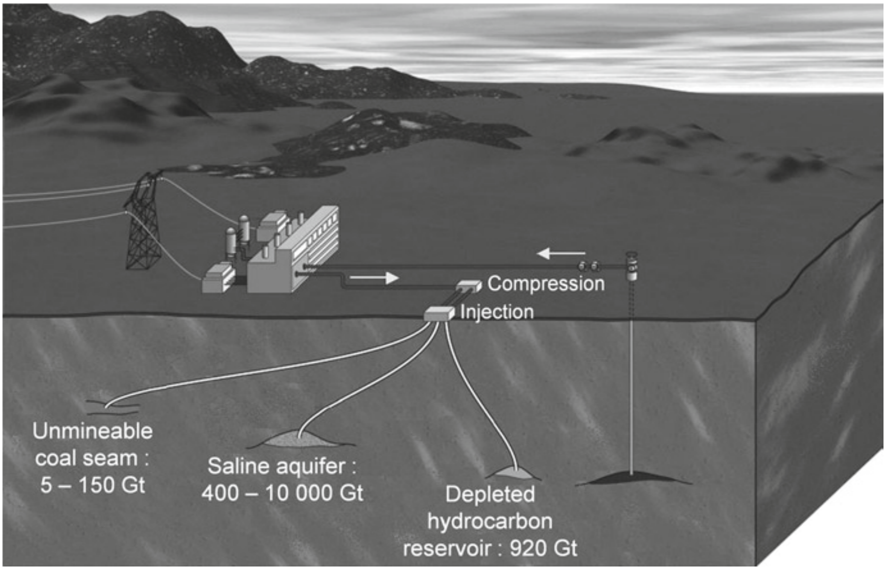


Fig. 12 General scheme of CO_2 injection from surface (© IFP)

have been put forward, but the capacity is limited and there is a high risk of leakage to surface.

During and after the injection phase, the well has to be sealed to prevent any migration of CO_2 to surface using preferential pathways. This will be achieved by placing cement and/or mechanical plugs in all parts of the well.

5.2 *Deep Drilling Technology to Access Reservoirs*

Deep drilling operations are generally performed by means of rotary drilling rigs, as shown in Fig. 13. In this technique, the hole is drilled by rotating a bit to which a downward force is applied. The hole can be initiated from the ground (onshore) or the surface of the sea (offshore), depending on the position of the targeted reservoir. Typically, the following operations are required to construct a production well: (1) put the drilling string in the hole and drill; (2) pull out the drill string and case the section; (3) perforate the casing to give access to geological formations from which formation fluids are to be collected; and (4) lower the production tubing in the hole and pump out the fluids. In the case of CO_2 disposal, the perforation technique will be used to allow injection. If the formation targeted for production or injection exhibits low permeability, the hydro-fracturing technique (performed by increasing the hydrostatic pressure in the well) can be used to create artificial fractures that will improve the fluid flow. This technique also enables the measurement of the in situ stresses.

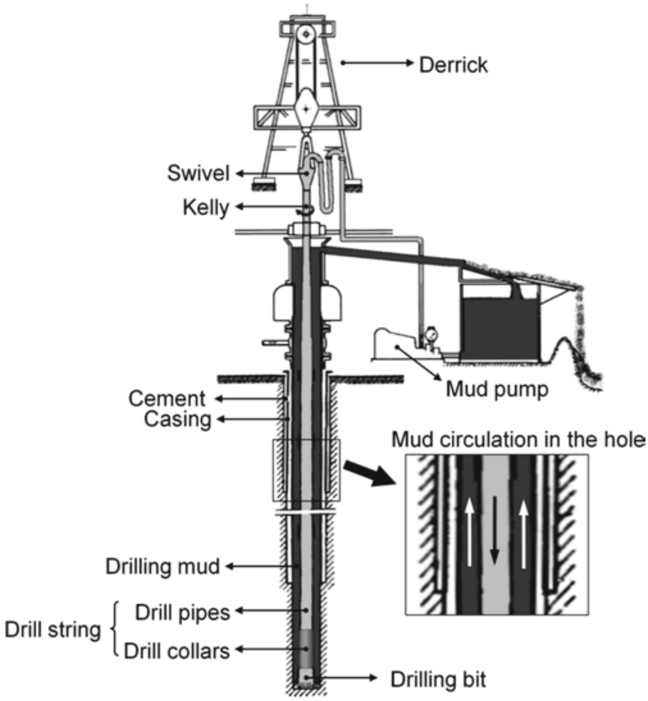


Fig. 13 Components of a typical rotary drilling rig

Nowadays it is possible to reach true vertical depths of 5,000 m and also to drill horizontally to distances of some 10,000 m from the vertical projection of the drill rig in the case of extended reach wells. Some experimental drilling projects such as the German Continental Deep Drilling Program (KTB) (Bram et al. 1995; Wohlgemuth et al. 1996), and the Kola Superdeep Borehole in Russia (Kozlovsky 1987) reached true vertical depths of about 10,000 m.

The main challenges for drilling operators can be summarized as follows:

- Choosing the suitable drilling bit in order to achieve the highest rate of penetration and the longest drilled distance or metrage;
- Ensuring the stability of the well during both the drilling phase by means of the drilling fluid and the production phase by use of cemented casings;
- Equipping the well to perform production operations.

5.2.1 Choosing the Drill Bit and Fluid

In rotary drilling, different cutting tools can be used depending on the mechanical properties of the geological formations (Bourgoyne et al. 1991; Moore 1981):

- *Rolling cutter bits* (or roller cones) are the most used bits and different technologies enable the drilling of soft to medium-hard rock formations;
- *Drag bits using polycrystalline diamond cutters* that can be used for soft to medium-hard rock with a reasonable abrasiveness;
- *Drag bits using surface set or the impregnated diamond technique* for hard to very hard rock formations.

Rolling cutter bits are at the lower end of the price range and impregnated bits at the higher end. Cost is thus an important factor in choosing the right bit to drill a given section of the well. To assess the theoretical performance of a bit, typical rock properties, including hardness, abrasiveness, mechanical behaviour (in terms of plasticity, for instance) must be measured.

Depending on the quantity of debris generated by the cutting tool, drilling fluid or mud should be used for cleaning, and the flow rate assessed accordingly. If the circulation is stopped, the fluid must be able to 'freeze' to avoid the settlement of cuttings and enable a good restart to circulation (thixotropic property). The usual drill fluids are water-based bentonite muds, oil-based muds and polymer-based muds. The bentonite-based muds are cost-effective, but they can cause clayey geological formations to swell. Oil-based muds are better for drilling such formations but they are forbidden in many countries for environmental reasons. In such cases, polymer muds can be a solution, even if they are expensive.

During drilling of each section, there is direct contact between the geological formations and the drilling fluid. Mechanical equilibrium is then provided by the hydrostatic pressure of the fluid. This is provided by the depth, on the one hand, and by the density of the mud, on the other. To ensure a suitable fluid pressure, drillers use additional materials like barium sulphate (barite) to increase density, but the fact that a very heavy mud can cause hydraulic fracturing of given formations must be taken into account. In such a case, the operation will be characterized by a loss of fluid in the formation, which could be very costly.

The drilling fluid has other functions: cooling the drill bit, avoiding ingress of formation fluids and guarding against mud loss by forming a *cake* (i.e. a thin layer of clay deposited on the wall of the well).

5.2.2 Ensuring Long-Term Stability and Sealing

Final support is achieved by means of a steel casing sealed to the walls by cement. First, the casing is introduced into the hole and then the cement is pumped into it to fill the annular space between the well wall and the casing. This sealing, when used with packers inside the casing, will avoid loss of fluids during the production phase (i.e. injection of CO_2). The casing will be designed to be strong enough to support the stresses from the ground induced by the well drilling. Deep wellbores are drilled in many stages or sections to ensure wall stability, depending on the geomechanical properties of the drilled formation. For instance, soft superficial formations should be drilled in large diameter and cased to avoid failure and enlargement when drilling deeper rocks. This obliges the driller to change to a smaller size of drill bit and casing when shifting from one section to the next (Fig. 13).

Different scenarios have been put forward to assess the CO_2 trapping mechanisms (see Sect. 5.1) and their evolution over time for as long as a million years (Benson et al. 2005). Because of the long time periods involved, well integrity in terms of mechanical behaviour (time-dependent stresses for creeping geomaterials) and corrosion (mainly of steel casing and cement) must be addressed carefully. In the abandonment procedure, special care then must be taken to use sealing plugs and cements that are resistant to degradation from CO_2. To tackle the problem of steel corrosion, the injection casing can be pulled out after operation and replaced by more resistant sealing materials (i.e. special cement).

5.3 Horizontal and Extended Reach Wells

From one onshore or offshore position, many targets can be reached using specific deviated well techniques: classical rotary drilling and use of deviating tools (i.e. whipstock), or steering motor with measuring while drilling (MWD) equipment (Bourgoyne et al. 1991). In the latter case, the drill string does not rotate and the downhole motor is operated by the pressure of the drilling fluid and is equipped with an electronic device, or MWD, to collect the data and transfer them to surface. This enables good real-time control of the trajectory of the well. The MWD can supply the following data:

- *Directional information*: taking real-time directional surveys using accelerometers and magnetometers to measure the inclination and azimuth of the wellbore, and then transmit the information to surface;
- *Drilling mechanics information*: provides information about the conditions at the drill bit, such as the rotational speed of the drill string, smoothness of the rotation, type and severity of any vibration, downhole temperature, torque and weight on bit measured near the drill bit, mud flow rate;
- *Formation properties*: when combined with logging while drilling tools, can take measurements of formation properties like density, porosity, resistivity, pseudo-caliper (measurement of the size of the hole), inclination at the drill bit, magnetic resonance and formation pressure.

Horizontal well technology is useful in storing CO_2 because of the high number of targets that can be accessed from one position of the drilling rig. The volume to be stored will also be increased if the trap (or reservoir) has a high horizontal extension.

5.4 The Particular Case of CO_2 Disposal in Coal Formations

CO_2 can be stored in combination with methane recovered from coal through ECBM. From a technical point of view, the method is similar to that used for petroleum reservoirs and deep aquifers. However, for economical reasons mining drilling techniques (smaller drilling rigs) can be tried.

Storing CO_2 in coal seams uses two physical mechanisms: filling the porous space constituted by fractures (cleats) and micropores, and adsorption (physical ability of fixing gas molecules) on the coal grain surface. This latter mechanism is typical of coal formations and other formations containing organic matter like shales.

The big challenge in terms of storing CO_2 in coal formations is the low permeability of this material and, hence, the difficulty of accessing large volumes. Some successful projects have been carried out in the world among which we can name the Alberta Research Council project in Canada (Gunter et al. 1997, 1998, 2005) and the Allison Unit CO_2-ECBM Pilot (Reeves et al. 2003). One recent trial, which was undertaken in Poland (the Recopol project in 2003–2005) (Pagnier et al. 2006) gave relatively poor results in terms of injected volumes and injectivity.

6 Comparing Engineering Issues Between Radioactive Waste and CO_2 Disposal

Table 1 summarizes some of the criteria we propose for use as a basis for comparison of the engineering issues involved in the geological disposal of CO_2 and RW. In both applications, some requirements are similar: the fluid propagation is (at least, partly) controlled by diffusion mechanisms and typical systematic studies (geophysical measurements, coring, laboratory testing, geomechanical and reservoir modelling) are necessary to assess the quality of the targeted medium and design the suitable disposal technique.

Regarding temperature, injected CO_2 can have a cooling action during the injection phase whereas RW will generate heat for a long time. In both cases, extensive study of thermo-hydro-mechanical coupling is necessary to take all possible effects into account: mechanical stability, water and gas migration, vapour formation, separation between openings.

However, some aspects are different. Because of the physical nature of the waste to be disposed of, CO_2 will be injected as a liquid (in its critical state) using deep drilling technologies as practised in the petroleum industry; RW, on the other hand, will be disposed of in mine-like facilities (using shafts and galleries). The depth of burial of RW will, in general, be shallower even if it is located deep enough to ensure isolation (ONDRAF/NIRAS 2001). However, if there are workers underground, the construction technique for RW disposal can be more hazardous, and the issue of handling hot materials must be addressed.

In both cases, an EBS, made of cement, steel and clay components, can be used. With RW disposal, the quantities involved are limited (from a few thousand to a million cubic metres) and the EBS is a complex multi-barrier system that isolates the waste from the host formation for a given span of time. For CO_2 disposal, the EBS is limited to the well, which is a small component of the big reservoir involved in the injection (quantities to be disposed of are several millions cubic metres).

The construction of the disposal site will create a damaged zone around the openings. This phenomenon may be of interest for CO_2 injection, as this can

Table 1 Comparison of radioactive waste and CO_2 disposals

Criteria	CO_2	Radioactive waste
1. Objective	Inject in existing porous medium	Create voids in host formations and secure them
2. Main transport mechanisms	Advection, diffusion, buoyancy	Diffusion
3. Retardation mechanisms	Sorption, mineralization	Sorption
4. Natural barrier	Caprock formation	Host formation mainly
5. Preliminary studies	Geophysics, coring, lab tests	Geophysics, coring, lab tests
6. Necessary properties of host and caprock formations	Porosity, permeability, thermo-hydro-mechanical (THM) parameters (elasticity, strength and plasticity, Biot's parameters, dilatation coefficients)	Porosity, permeability, THM parameters (elasticity, strength and plasticity, Biot's parameters, dilatation coefficients)
7. Construction method	Petroleum technology: deep drilling	Mining technology: shaft and galleries
8. Engineered barrier system (EBS)	Cement plugs with or no steel casing: limited control on the well	Multi-barrier concept: container, shroud(s), backfilling (cement, clay)
9. Geomechanical modelling	Stability of wells by mud or casing	Stability of created cavities and lining assessment
10. Reservoir modelling	Assess injected volume and sealing capacity	Migration of radionuclides in the host formation
11. Depth of burial	Generally from 800 to 1,000 m (injection at supercritical state)	Generally a few hundred metres or more
12. Temperature	Injected fluid cooler than host formation	Heat generation by the waste
13. Risk of hazard during construction and disposal	Limited, no workers underground	Higher because of the presence of workers
14. Relevance of disposal with respect to produced volumes	High capacities needed (millions of tonnes) Can be achieved by combining different reservoirs	Lower quantities (from few thousands to more than a million cubic metres)
15. Role of a damaged zone around the opening	Increases or decreases permeabilities Controlled by mud density	Generally increases permeabilities Controlled by the digging technique
16. Long-term sealing of the disposal	Favoured by trapping mechanisms Issues: leakage through the caprock, casing corrosion	Depending mainly on resistance of EBS Issues: corrosion of the shroud
17. Safety assessment	The methodology is the same Very long timescale phenomena (thousands of years to a million)	

increase the permeability of the host formation (fracturing or dilatancy). However, a decrease in permeability is also possible, particularly in coal seams (swelling). It is therefore important to control the mud density during the drilling phase. When an RW disposal site is being constructed, permeability of the host formation will generally increase due to the damaged zone, the size of which should be controlled through the digging technique (sequence of dig and support).

The long-term sealing of the reservoir is an important issue. This will be favoured by trapping mechanisms for CO_2 disposal whereas the EBS will play a major role when disposing of RW (especially when the host formation, for instance, granite, is not very tight). For RW, corrosion of the metallic shroud may occur and lead to migration of radionuclides into the host formation. For CO_2, the corrosion (or other chemical mechanisms) of the cemented steel casing is also an issue, but this can be avoided by pulling the casing out after injection and before cementing and plugging. Moreover, the leakage through the caprock (except for depleted reservoirs that exhibited sealing during geological times) must also be addressed.

For safety assessments, the same approaches are used, and studies have been performed for spans of time of up to 70,000 (RW) to a million (CO_2) years, taking into account different scenarios. Some criteria can be set for engineering approval and licensing: quality of the host formation (physical parameters, modelling of transport mechanisms), disposal and sealing technology (sequencing and security during operations and after abandonment), quality of the EBS components (resistance to corrosion, etc.). The monitoring system will play a major role regarding the long-term safety (Brunskill and Wilson 2011).

7 Conclusions

The chapter focuses on engineering issues related to the challenges of the geological disposal of both RW and CO_2. In both cases, engineering techniques exist to access deep geological formations with suitable characteristics, dispose of the waste and ensure long-term sealing. Engineering studies to design the disposal are similar: sample collection, laboratory testing, in-field qualification of geological formations, geomechanical and reservoir modelling. In fact, the displacement of potentially polluting fluids in the porous media needs to be assessed and the geological material both for resistance to excavation techniques (i.e. mechanical digging) and long-term stability to be characterized.

The RW repositories use mining techniques with some specificities like the handling of hot materials by workers underground during the disposal operations. The hosting geological formation is to be as impermeable as possible and the residual voids will be filled by a low permeability material (clay or cement) that will contribute to the EBS intended to limit the diffusion of radionuclides.

CO_2 disposal will use techniques developed in the petroleum field when targeting deep reservoirs; this means deep drilling with deviated trajectories. For long-term stability and sealing, there is a need to install cemented casings with sealing plugs in the well. One of the challenges for the future is the durability of this system in the presence of CO_2; special cements are being developed and it is possible to remove the casing before abandonment. The long-term leakage through the natural barrier or caprock must be addressed carefully.

In this chapter we have presented the main transport mechanisms of pollutants and the parameters needed to characterize the potential host geological formations. The methodology for designing and constructing the underground openings was then presented, with an emphasis on the techniques to be used for the disposal of RW and the CO_2. In Sect. 6, we have applied some criteria to compare the engineering issues related to the two approaches, and have accompanied this with a number of relevant comments.

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