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Disposal of Low- and Intermediate-Level Radioactive Waste

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Abstract

As for isolation of high-level radioactive waste by use of smectite clay it serves very well also for hindering radionuclides from low- and intermediate-level waste to contaminate groundwater. It can be used for minimizing groundwater flow through and along waste packages and for providing them with ductile embedment for eliminating the risk of damage caused by displacements in host rock or concrete vaults. The clay can have the form of liners placed and compacted on site over vaults constructed on the ground surface, or consist of compacted blocks of clay granules that are tightly placed around waste packages in underground drifts and rooms. In either case the initially incompletely water saturated clay will swell in conjunction with water uptake until tight contact with the confining medium has been established. The clay seals must be sufficiently dense to fulfill criteria set with respect to hydraulic conductivity and swelling capacity, paying due attention to the salt content in the porewater. Their physical and chemical stabilities must be acceptable in short- and long-term perspectives, which is a few hundred years for most low-level wastes up to tens of thousands of years for long-lived waste.

Keywords: Low-level radioactive waste (LLW), smectite clay, radionuclides, underground disposal of radioactive waste, mineralogy of clays.

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1. Introduction - Scope

The purpose of the paper is to describe concepts for disposal of low- and intermediate-level radioactive waste with special respect to the waste-isolating role of clay barriers of expandable type, and to examine their evolution and function in repositories on-ground and underground, paying attention to the physical and chemical stability of such seals and to the hydraulic performance and mechanical stability of the confining medium. Interested readers are referred to references like [1] for a wider overview of techniques for disposal of low- and intermediate-level radioactive waste.

2. Low- and intermediate-level radioactive waste

2.1 Basics

Low-level radioactive waste (LLW) contains only about 1 % of the total radioactivity generated over the lifetime of a nuclear power plant, but can represent 90 % of the total volume of radioactive waste emanating from it. Since low-level waste cannot be disposed of as ordinary house-hold waste it is segregated, measured for radioactivity, processed and placed into strictly engineered and monitored waste disposal facilities, as with intermediate level waste.

There are several options for disposal: landfill on-ground and underground containment in newly constructed repositories or in certain types of abandoned mines. For low- and most intermediate level waste (ILW) that this paper also deals with, isolation from groundwater and the biosphere is required for a much shorter period - a few hundred years – than high-level waste. The major goal is to provide effective isolation but also to find the required space for disposal. The need for such space is continuously growing and in countries with limited available ground surface for disposal, like Japan, Switzerland and the UK, one may have to use underground disposal. This raises the problem of finding suitable rock with low groundwater percolation rate and sufficient mechanical stability. These properties are also important for underground disposal since rain- and meltwater percolating sites where LLW and ILW are stored will migrate into the underground and reach the bedrock directly or via soil layers. Radioactive contamination of the groundwater may take place in either case.

The aim of the paper is to describe major physico-chemical processes that are involved in the maturation of clay seals, i.e. water saturation, swelling/consolidation, shear strain under own weight, and in migration of radionuclides within and through smectite clay barriers. It will also touch on the subject of disposal of highly radioactive wastes [2].

2.2 Categorization and classification of LLW and ILW

Radioactive materials and wastes are obtained as a result of use of the various technologies employing nuclear devices. Harmful radiation from radioactive sources can be traced to direct ionizing radiation from α and β particles. γ rays, on the other hand, are considered indirect ionizing radiation. Since ionizing radiation removes bound electrons from the orbit of an atom in interaction with the atom, it is therefore capable of changing the molecular structure of the biological cells that make up living organisms. The effects of exposure to ionization radiation requires one to distinguish between long-term and acute radiation exposure. Hence, the intensity and effects of radioactivity on humans make it necessary to perform measurements for determining (a) the strength of the radioactive source, (b) the energy of ionization radiation, (c) the radiation dosage, (d) the absorbed dose, and (e) the length of time during which the person or animal has been exposed to the radiation dosage.

The International Atomic Energy Agency (IAEA) classification scheme of year 2009 contains 5 categories of radioactive wastes as follows [3]:

- Exempted Waste (EW) – "Activity levels at or below national clearance levels which are based on an annual dose to members of the public of less than 0.01 mSv". The SI unit of dose equivalent sievert (Sv) is used in place of the older rem (Röntgen equivalent man). 1 Sv = 100 rem,
- Low and intermediate level waste (LILW) – "Activity levels above clearance levels and thermal power below about 2 kW/m^3",
- Short-lived LILW (SL-LILW) – "Restricted long-lived radionuclide concentrations (limitation of long-lived alpha emitting radionuclides to 4,000 Bq/g in individual waste packages and to an overall average of 400 Bq/g per waste package)". The SI unit of radioactivity, Becquerel (Bq), defined as a unit of radioactivity equal to one unit of nuclear transition or disintegration, is used in favour of the previous conventional Curie (Ci) expression for the unit of activity of a radioactive material. 1 Ci = 37 GBq,
- Long-lived LILW (LL-LILW) – "Long-lived radionuclide concentrations exceeding limitations for short-lived LILW". The same techniques for disposal of HLW are generally recommended for this class of waste,
- High level waste (HLW) – "Thermal power above about 2 kW/m^3 and long-lived radionuclide concentrations exceeding limitations for short-lived LILW". Geologic containment systems are recommended for disposal/isolation of this class of wastes.

The IAEA scheme now includes 6 categories of radioactive wastes, the aim of which is not only to update the classification scheme based on available information, but also to offer guidelines for management/disposal of the wastes. Whilst they have kept the designation of exempt waste (EW) for consistency purposes, they offer the observation that once the waste has been cleared from regulatory control, it is no longer considered as a radioactive waste. The biggest set of modifications in

classification in the newer scheme lies in the categories of LILW. All the three previous categories of LILW – LILW, SL-LILW, and LL-LILW – have been replaced with new designations and criteria as follows: VSLW for very short-lived waste, VLLW for very low-level waste and LLW for low level waste. In addition, there has been a clear distinction made between low level (LLW) and intermediate level waste (ILW) with the addition of ILW as a separate and distinct category. The designation of HLW remains consistent with the previous sets of considerations.
Referring then to the USA, five general categories of radioactive waste are specified:

- HLW can be spent nuclear fuel from nuclear reactors and HLW from the reprocessing of spent nuclear fuel, and can come from transuranic radioactive waste (TRUW) emerging i.a. from defence programmes,
- LLW comes from naturally occurring radioactive material and some industrial practices, often called NORM and TENORM. The latter is LLW and ILW found in many waste streams, scrap metal, sludges, slags, and fluids, and is discovered in industries traditionally not thought of as affected by radionuclide contamination, like the petroleum industry. The decay products of Radon are the largest source of natural radioactivity man is exposed to,
- LLW can be mill tailings of uranium ore.

The American scheme does not include ILW, which is interpreted as "radioactive waste not classified as high level radioactive waste, transuranic waste, spent nuclear fuel, or by-product material as defined in a section of the Atomic Energy Act of 1954". It states that some LLW can be as radioactive as certain HLW, hence demonstrating that there is no global agreement on classification of radioactive waste. In this paper we have generalized ILW to comprise of any "cold" radioactive waste with high solubility and low sorption ability, which is in agreement with IAEA's statement that disposal sites for low- and intermediate-level wastes are in operation with intermediate level waste and low-level waste disposed of in the same facility. These facilities are commonly at or near the surface – for which we will use the term on-ground in the paper – while some intermediate level waste with long-lived radionuclides is disposed at larger depths, for which we will use the term underground disposal.

2.3 Liberation and migration of radionuclides: Protection from radioactive materials

Protective measures against emitted radioactivity (radiation) from materials and substances are provided by *shielding*. Since the half life time of radionuclides range from a few seconds to tens to hundreds of thousands of years, shielding techniques and containment facilities need to be designed and constructed to provide for safe shielding against released radionuclides for the required number of years. The important issues to be considered include (a) the kinds of radionuclides to be shielded, (b) the level of radioactivity (i.e. intensity), (c) the radioactive source or form of material generating the radioactivity, (d) the type of shielding and containment technique, and (e) the required life-spans of the shielding containment technique and types of disposal.

Shielding means protection against radiation posed by α, β particles and γ rays. α particles cannot pass through the sheet of thick paper and lead and aluminum sheets are effective as shields against β particles. Concrete is effective as a shield against γ rays, if it is at least 14 cm thick. Lead shields thicker than 2.5 cm are most effective in shielding against γ rays.

Containment means encapsulation in concrete, bituminous materials, and aluminum. The need for encapsulation is for ensuring that effective shielding is obtained [4]. Where deemed desirable, disposal of radioactive materials can be made by using deep geologic disposal techniques such as those used in the containment and isolation of high-level radioactive wastes. Examples and requirements for such procedures can be offered by abandoned mines [5].

Malfunction of the containment can be caused by corrosion or breakage, or both, and can result from natural chemical processes or changes in the chemical environment, such as inflow and permeation of the repository by aggressive groundwater or by chemical solutions resulting from human activities. Mechanical damage can be caused by meteor impact, terrorist actions, and warfare as commented on below.

The energy released by meteor impactor is a function of its diameter, density, velocity, and angle of strike as stated by the U.S. Geological Survey. The velocity is said to be at least 17 km/s and the most probable impact angle is 45 degrees. It has been estimated that stony asteroids with 4 m diameter reach the Earth about once per year and that meteors or asteroids with 7 m diameter approach Earth every 5 years. They have the kinetic energy of the Hiroshima nuclear bomb, i.e. 16,000 tons of ordinary TNT explosives, but commonly explode and become vaporized in the upper atmosphere. Asteroids with 50 m diameter reach the Earth once every thousand years and large fragments from them hit the surface of Earth. Even larger ones, creating craters with diameters larger than about 1 km, have an estimated frequency of one per 5000 years [6].

In modern time the risk of terrorist attack on on-ground LLW/ILW repositories cannot be ruled out: placement of strong explosives on the top of such a repository or deliberate dropping of bombs on it for damaging vaults and releasing and dispersing radioactivity has to be considered. If 250kg bombs with strong explosives fall on an on-ground repository craters with several meters depth and diameter can be created, requiring repair under difficult conditions.

There are two major cases to be considered, i.e. bombs penetrating ground without detonation, and cases in which the bomb explodes at the depth at which it is intended to explode. Both cases have been treated in numerous technical and scientific papers, still leaving a number of questions unanswered, like the importance of layering of soil and the time- or depth-related triggering of the explosion, not to mention future development of horrifying bombs of even stronger destruction capacity. Here, we will mention the simpler case of minor detonation and indicate how a bomb exploded at a certain depth affects the surrounding ground. This is made by referring to a relevant study by Lacoste [7], who examined in detail the effects of bombing of dikes belonging to the extensive system of dikes for creating water reservoirs in Vietnam. The most frequently used bombs in the attacks weighed 230 to 450kg causing craters with 6-7m depth and somewhat more than 10m in diameter in the dikes, which were made of clay/sand/silt mixtures. These had to be repaired by using similar material. Repair had to be made also of the series of cracks that were caused by the shocks affecting the ground within about 50m distance from the explosions and that caused loss of the water-sealing potential of the dikes. Disturbance of the continuity of natural clay layers below and adjacent to the dikes, caused by the shock waves, generated erosion below the dikes and large-scale piping, leading to undermining of the remaining and repaired parts of the dikes. Much of the damaged system was close to the Red River and the risk of sudden break-through of river-water made repair difficult and with poor results.

The same would happen to on-ground repositories with LLW and ILW where repair would have to be made also with radioactive shielding in the case of extensive damage in the first hundred to two hundred years after finalizing repository construction work.

Like HLW and LLW, ILW must be encapsulated in containers for safe handling during transport and placement and for equipping the waste packages with a basic protection against mechanical damage. Contact with air or water would naturally make released radionuclides migrate and become disseminated to the surroundings. Safe handling implies that personnel must not be exposed to any form of radioactivity, especially not gamma radiation, requiring in most cases remote handling by employing robot technique superintended and documented by filming. The primary engineered barrier to spread of radionuclides is a container of concrete or steel that can fracture or corrode if stored in humid atmosphere or in contact with stagnant or flowing water. In these cases, which represent, in particular, underground ILW disposal, release of radionuclides to water that has come in contact with the waste, takes place to an extent and at a rate that are determined by the solubility of the radionuclides and the mobility of the water. Radionuclides migrate by diffusion away from a leaking waste container, creating a plume if the water is stagnant, or following water that migrates in channels in rock fractures, in natural soil underground or in backfills, if there is a hydraulic gradient in the system. Placement of most ILW is best made by dry underground storage at moderate depth, which, however, implies very slow but inevitable wetting until complete water saturation is reached. In contrast, on-ground storage in dry desert climate with a top clay liner as hydraulic barrier can leave the waste unsaturated for very long periods of time as exemplified in the paper. As said, this type of storage is, however, very sensitive to damage and to very strong winds prevailing in deserts since they can cause exposure of the waste and lead to wind erosion of the waste packages and dispersion of radionuclides in the air. This can cause radioactive contamination of very large areas.

3. Concepts for disposal or storage of LLW and ILW

3.1 Principles

IAEA gives general recommendations on how *Near surface options* and *Geologic options* shown schematically in Figure 1 can be materialized. Considering the fact that both concepts imply involvement of the geosphere makes local geology an essential factor in this context.

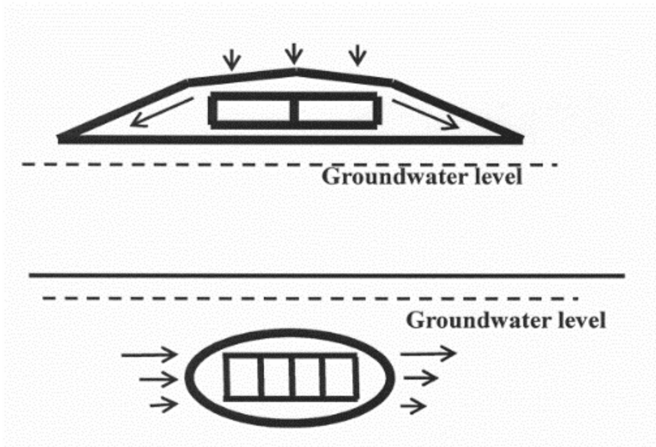

Figure 1: Two options for LLW and ILW disposal with clay liners. Upper: on-ground disposal ("near surface option"). Lower: underground disposal ("geologic option"), both requiring clay isolation of concrete vaults containing waste. Arrows indicate water flow.

3.2 On-ground disposal

3.2.1 Near surface landfill

The very large amounts of very low-level waste resulting from current use and decommissioning of nuclear power plants and clean-up operations, as well as various industrial and medical activities, can suitably be disposed in near surface repositories in the form of landfills with very limited shielding (Figure 2). This can be a cheap and sufficiently safe option according to IAEA but requires that containment of the radionuclides in the waste is certified by placing it above the groundwater table and by minimizing or eliminating the risk of rainwater inflow and percolation by covering the fill with a sufficiently impervious clay layer. Other types of soil such as coarse-grained crushed crystalline rock material for erosion protection and for providing support to waste container assemblies are also used. Such simple ways of isolating waste with very limited amounts of long-lived activity can be acceptable provided that adequate waste acceptance criteria (WAC) and quality control ensure that the radionuclide content will not be dispersed and cause contamination of the surroundings. Other criteria are that clay liners and fills must not undergo freezing/thawing since this can ruin their homogeneity and low permeability. Overburden of coarse rock fill is required since terrorists or warfare can cause enough damage to release radioactive dust. This speaks in favour of underground disposal of all radioactive waste.

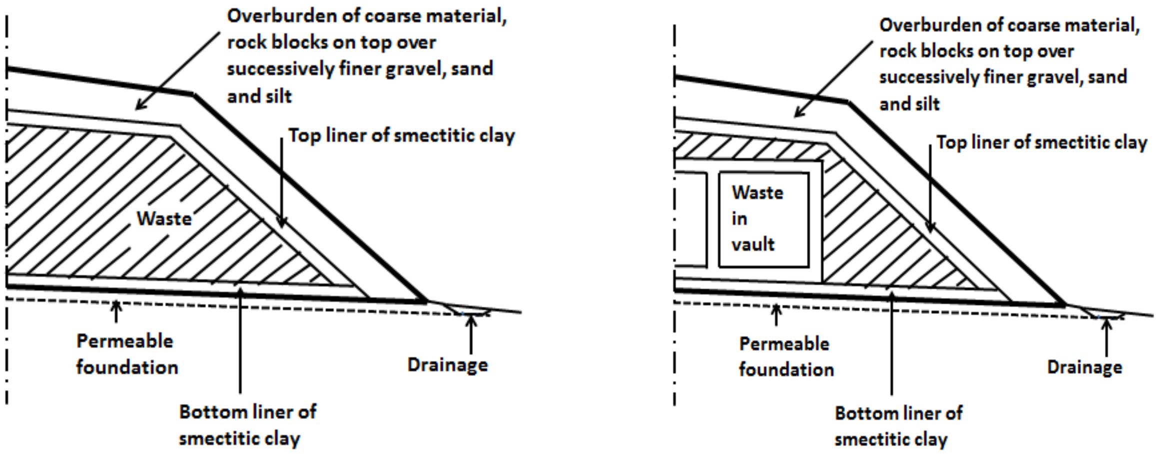

Figure 2:Schematic sections of on-ground repositories for LLW and ILW. Left: Simple landfill for very low-level waste. Right: Ordinary LLW and ILW placed in concrete vaults [1].

<u>LLW with some long-lived activity</u>

Waste with long-lived activity requires construction of rather complex engineered barriers, exemplified by the right part of Figure 2, and elaborated sealing and stringent requirements on the waste treatment and packaging (cf. [8, 9]. This can be achieved for disposal on-ground - the landfill option - or in facilities close to the ground surface according to concepts that have been used in the US and in European countries.

This option, which requires location above the groundwater level and effective drainage of the site in question, can have the form of concrete vaults divided into separate compartments covered by a waterproofing layer of clay, in turn covered by erosion-resisting coarser material. Implemented engineered surface repositories of the vault type has involved solution of geotechnical problems for being constructible and for guaranteeing stability and effective reduction of the amount of water that could contact the waste. According to IAEA such facilities are commonly intended for disposal of short-lived waste with the activity of long-lived isotopes in the range 400 to 4,000 kBq·kg^{-1}. According to usual criteria monitoring is required after closure during the period of institutional control, i.e. the WAC, that limits the type, concentration and quantity of radionuclides allowed in waste packages, reflecting the limited retention capability of this type of disposal.

3.2.2 Stability and hydraulic performance

The top clay liner to the right in Figure 2 will be taken here as an example of how this and similar concepts evolve with respect to stability and waste isolation potential. It has been examined with respect to its evolution from the initial state of placement and compaction, over a period of several hundred years, by Al-Thaie *et al* [10] and has been approved by IAEA for use in Lithuania [9]. The main issues are the stability of the leaning layer and its ability to retard water percolation. The clay material was assumed to be composed of crushed and milled smectitic Iraqi clay mixed with desert quartz sand, the mixture being termed "Green clay" with 64% montmorillonite and having a hydraulic conductivity of E-10 m/s and a swelling pressure of 20kPa (cf. Figure 3). The density at water saturation was taken as 1,700kg/m^3 (1,100kg/m^3 dry density) for calculation of slope stability and percolation.

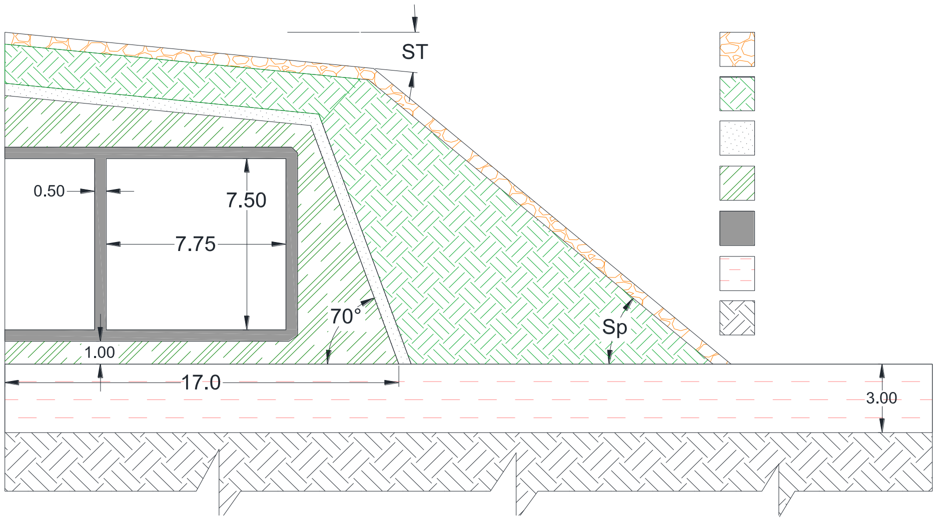

Figure 3: Proposed LLW/ILW repository with vaults Dimensions in meters (After Al-Thaie).

<u>Stability issues</u>

The safety factor of slope stability was evaluated by Al-Thaie for different slope angles (S_T) for the top liner system and (S_P) for slip in the overlying coarse-grained protection layers [10]. The assumed inclinations were, for S_T: 0.1, 2.9, 5.7, 8.5 and 11.3^o, and for S_P: 27.5, 30, 32.5, 35 and 37.5^o, maintaining the steep slope of the vault-surrounding clay fill at 70^o in the analyses. The Mohr-Coulomb failure criterion and model were applied [11], assuming drained conditions for all materials including concrete, which was taken to be linearly elastic. For the clay liner the laboratory-derived effective shear strength parameters c'=10kPa and φ'=20^o were utilized in the stability analyses.

The safety factors for different S_T and S_P values are shown in Figure 4. For S_P=30^o the safety factor was found to be about 1.5 with insignificant impact of S_T. For all components being initially in air-dry condition, which also had to be considered, the safety factor was higher since the shear strength parameters significantly exceed those for complete saturation with water.

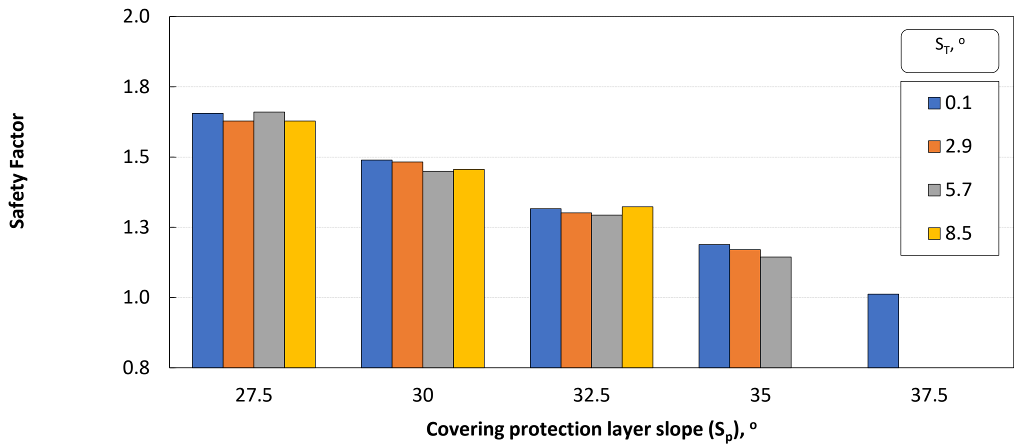

Figure 4: Safety factors derived from slope stability analysis for different angles of the slope of the top liner system (*S_T*) and of the slope of covering erosion-protective layer (*S_P*), [10].

Creep testing showed that primary creep with attenuating strain rate for the respective safety factor will not lead to "secondary" creep implying constant strain rate and ultimate failure. Figure 5 shows the creep behaviour of water-saturated clay samples ("Green clay", an Iraqi brand) exposed to step-wise increased axial pressure in unconfined compression tests. The strain for each load step beyond the first one, was largely elastic and larger for the 50% clay mixture than for the one with 25% clay, which is explained by the higher shear resistance of the latter. The stress/strain/time curves indicate a strain rate at the end of each loading step of E-8 s^{-1} to E-7 s^{-1} representing primary, retarded creep, [12,13] for stresses lower than about 70% of the load at failure (Safety factor 1.42), while overstressing and initiation of failure occurred at 90% of the failure load (Safety factor 1.11). An important fact is that the strain rate was similar for both clay mixtures, suggesting that the rheological behaviour in bulk was controlled solely by the clay component.

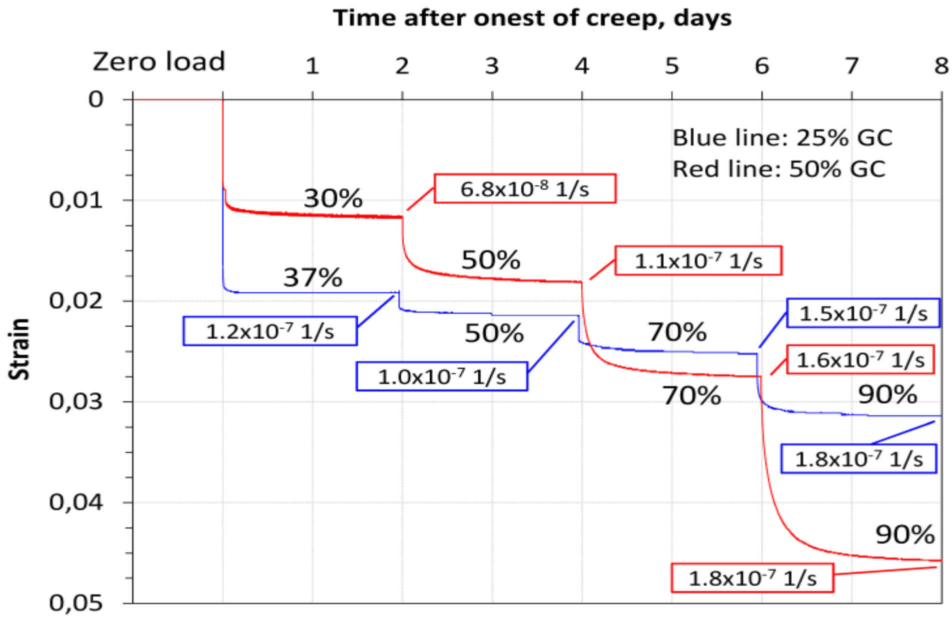

Figure 5: Creep behaviour of mixtures with 25 and 50% "Green clay" for step-wise loading (ratios indicate load increments in percentage of the unconfined compressive strength). The numbers in frames indicate, in potential form, the strain rates at the end of each loading step [10]. The stabilizing effect of extra sand, represented by the blue curves in the diagram, is obvious.

3.2.3 Hydraulic performance

Wetting, drying and percolation of waste-filled vaults

Cyclic hydration/dehydration implies that water retention, hysteretic behaviour and phenomena of unsaturated hydraulic hysteresis play a major role [14]. Water penetration in swelling clay can either be of finger flow path type (loose structure) or in the form of diffusive migration implying coherent microstructure at high densities. The wetting front advance (WFA) is a function of the initial soil density and percentage of expandable clay minerals, as well as of the water pressure and geometrical and boundary conditions. For smectitic clay, the WFA of highly compacted confined clays is much slower than of clays of low-density despite the lower porosity of the dense ones.

In desert climate, dehydration of clay liners will be a dominant process in drought seasons, causing risk of fissuring and fracturing. Cracks can be filled with frictional material emerging from the filter materials in the layers overlying the top liner, hence reducing the "effective" liner thickness required by the designers [13, 14]. Naturally, a sufficiently thick overburden over the top liner can eliminate or minimize the impact of temperature and moisture fluctuations on the formation of desiccation fissures and fractures. One furthermore realises the role of the self-healing capacity of the smectite component of mixtures or suitably graded natural

smectitic clay upon wetting: smectite granules and aggregates confined between densely grouped silt and sand grains live their own life of expansion and shrinkage with a minimum of creation and closure of fine cracks emerging from shrink–swell cycles. Self-healing ability can be lost by precipitation of cementing agents like air-born salt and silt/clay fines that become infiltrated at occasional inflow of water.
The hydrological evolution of a just completed top liner system was predicted by Al-Thaie for "desert" cases by use of the numerical codes HELP 3.80 D version and HELP 3.95D [15,16].The water balance was expressed mathematically in terms of water referred to as "in", "out" and "stored" within the system for a given period of time:

$$I = P - R - \Delta W_{surface} - \Delta W_{plants} - \Delta W_{soil} - ET - L \tag{1}$$

where:
I: infiltration
P: precipitation (rain or snow)
R: runoff
$\Delta W_{surface}$: change in water storage on the liner surface
ΔW_{plants}: change in water storage in covering vegetation
ΔW_{soil}: change in water storage within the liner
ET: evapotranspiration
L: drainage

For calculating unsaturated water flow in top clay liners and overlying drain layers Al-Thaie used codes like VADOSE/W [17]. It simulates coupled physical processes of heat, mass and vapour flow in porous media.

Numerical modelling

Al-Thaie's hydrological simulations using HELP 3.95D of permeation of top liners in arid climate showed that the water leakage decreased continuously by increasing the slope angle and the clay thickness. For a 0.5 m thick liner with the slope angle 5.7° the average annual leakage was found to be 2.6 mm/year (2.6 litres per square meter and year), which is within the limits recommended for liners over hazardous waste landfills [18]. An inclination of 5.7° was found to be required for avoiding water pounding over the top liner system.
Al-Thaie's predictions by use of the more advanced code VADOSE/W based on precipitation and temperature data derived from official sources showed that the daily leakage through the bottom liner would be, at maximum, 1.29E-3 and 1.33E-3 mm/day for the initially saturated (wet) and unsaturated (dry) cases, respectively. Figure 6 shows that both downward liquid flow, i.e. leakage, and upward flow toward the liner in desert climate take place driven by pressure and suction forces. For the uppermost part of the liner the degree of water saturation dropped from initially 78 % to less than 20 % in the considered eight-year period, while for the lower part it went down from 70 % to about 30 %. No net permeation of the liner

would hence take place and only internal small-scale moisture movements would occur.

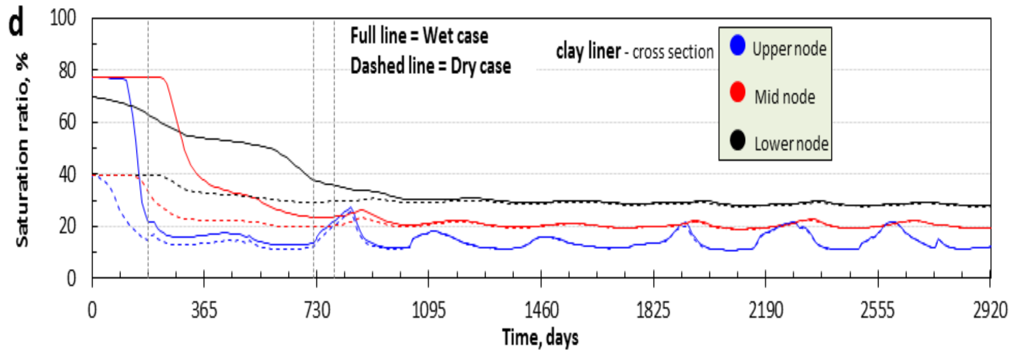

Figure 6: VADOSE/W simulations for wet and dry conditions of the top liner in arid desert illustrate the expected variation in saturation ratio in the upper part of the top liner ("d"), [10].

By extending the assumed time of performance to 300 years the calculations showed that the degree of saturation of the clay liner will continue to decrease with time and ultimately reach about 9 % in the top part. The top liner is the first defense line with the reinforced concrete vaults as second defense line, a third one being represented by the bottom liner if the vaults would become water-filled. This means that the top liner controls the whole wetting/drying cycle of the facility and that it should be designed to be the least permeable barrier. The bottom liner should have a dry density of at least 1,700 kg/m^3, which, for 70% clay content, would have a hydraulic conductivity of less than E-10 m/s for percolation with moderately salt waste-water [11]. The swelling pressure for the case of complete saturation with low-electrolyte waste water would not cause practically important upheaval of the vault system since the effective vertical pressure would almost balance the swelling pressure of about 300-400kPa. In practice, cation exchange by uptake of Na-replacing polyvalent cations from the waste will reduce the swelling pressure and further reduce the risk of upheaval.

In examining long-term performance of this type of repository in dry areas one would have to consider chemical effects of contacting smectite clay and concrete but since both of them are largely unsaturated for a considerable period of time one can refrain from this. This is also motivated by the fact that the chemical activity of modern concretes based on use of low-pH cement and with talc as fluidizer, is very low [1].

In summary, repository concepts of on-ground type located in areas with low annual rainfall can keep radioactive waste dry as were it stored in a mausoleum. Further advantages are:

- Simple construction principle,
- Low construction cost by using natural smectitic clay material with no other treatment than drying (in air), crushing and removal of large chunks; or by excavation of undisturbed blocks of virgin homogeneous natural clay with desired properties for direct placement in the repository,
- Sufficient isolation of dry waste in any climate zone, and excellent isolation in arid climate.

Disadvantages are:

- Placement and compaction of clay are weather-sensitive construction operations in humid climate and at unexpected rainfall,
- Difficulty in guaranteeing uniform quality of clay material and compacted clay with respect to water content and density. A variation in smectite content of +/- 5 percent units has to be assumed in performance assessments.

Safety assessment and management

Safety, respecting impact on human health from fugitive radionuclides, is a major criterion. Indicators are radiation doses exposed to human and other bio-bodies, and accumulated measurable amounts of radionuclides in the environment. In order to confirm safe conditions, it is essential for repository designers to predict the accumulation of radionuclides in environment elements in both short- and long-term perspectives. For this purpose, the flow rate of water carrying radionuclides, and diffusive migration of radionuclides in geologic environment must be predicted and considered.

For surface repositories a period of active institutional control follows repository closure in order to signal possible malfunctioning, human intrusion and damage to the facility. The idea of such active control is to maintain it long enough for the radioactivity to decay to values considered no longer a hazard, which should be in the interval of 300 to a few thousand years. This is not possible in practice because the sensor systems would not be reliable over time and hence give false information on possible migration of released and migrated radionuclides, and because no organization would be operative in such period of time [2]. One simply has to rely on theoretical modellings based on laboratory tests of the clay material. For this purpose, we make use of the hydraulic conductivity K, which gives us the flow rate according to Darcy's law: $v=Ki$, where i is the hydraulic gradient. This gradient should not exceed 100m/m in laboratory tests, while for a top liner it is usually on the order of 10m/m.

The influence of the thickness of the clay liner is recognized by varying the hydraulic gradient, which was taken as 10 m/m[6] in preparing the diagram in Figure 7. The impact of a change in density on the flow rate of radioactively contaminated percolates is directly derived from it.

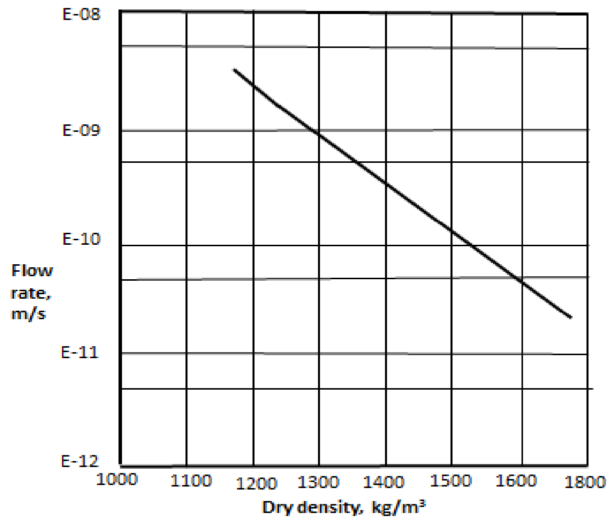

Figure 7: Approximate average percolation rate of water passing through a 0.5 m thick clay liner of clay with 20 % montmorillonite content as a function of the dry density. The assumed hydraulic gradient is 10 m/m.

The diagram shows that the rate of permeation and hence the corresponding rate of mass transport of radionuclides are significantly altered by deviation from the designed dry density of the clay layer 1,500-1,600kg/m^3 to, for example, 1,300-1,400kg/m^3. The flow rate would rise by more than one order of magnitude for such a reduction in dry density, i.e. from about 5E-11 m/s to about 5E-10 m/s**.** The safety factor F with respect to groundwater contamination would hence drop in proportion to this difference, i.e. from an initial value F_1, that depends on the hydraulic gradient, to a value $F_2=0.1F_1$. For $F_1= 30$ one would get $F_2=3$, while for $F_1=3$, implying threefold safety, there would be no safety at all, etc.

[6] m/m means flow rate per meter flow under a pressure difference in piezometric height in meters

3.3 Underground disposal

3.3.1 General

For some ILW and other radioactive wastes with long-lived radioactivity that do not produce heat, underground disposal, illustrated by Figure 8, is generally preferred or required by national laws. The main difference between waste disposal on-ground and underground is that the latter usually gives earlier inflow of groundwater into the repository because of the comparatively high piezometric pressure, hence causing earlier saturation of the waste and faster release of soluble radionuclides to the surroundings than in on-ground repositories. On the other hand, the last-mentioned disposal concept suffers from the facts that engineered barriers of metal, i.e. waste packages and steel reinforcement of concrete, start corroding early, giving off hydrogen gas by infiltration of oxygen-rich water, and that high hydraulic gradients cause dispersion and erosion of engineered soil seals, especially clay liners.

Valuable properties of underground waste disposal are firstly that groundwater percolation is very slow after saturation of the disposal space and that the risk of human intrusion and terrorist attack is largely eliminated. The risk of liquefaction by seismic events is also significantly lower than for on-ground disposal because of the much more effective confinement. Once the underground waste fill has been fully water saturated the rate of groundwater percolation and associated dissemination of released radionuclides will be significantly lower than for on-ground disposal because the hydraulic gradients operating at depth are much lower than those prevailing in the cover of a disposal facility on-ground.

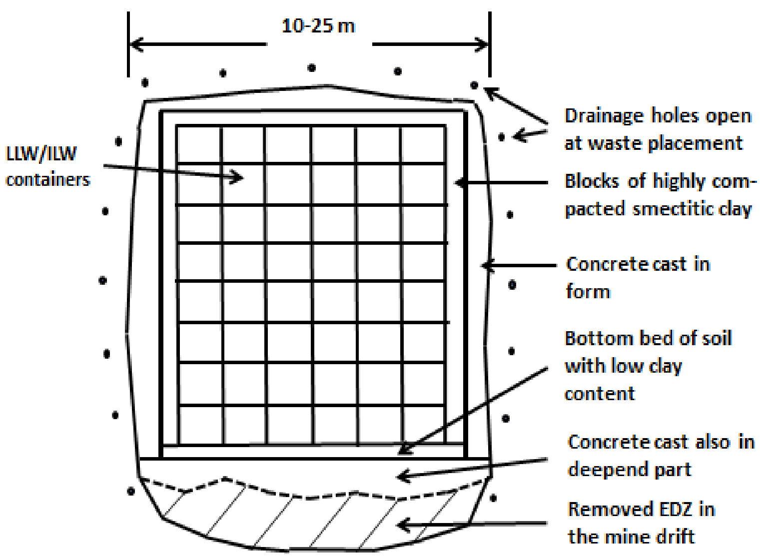

Figure 8: Principle of effective isolation of LLW/ILW in large blast-excavated rooms or in abandoned mines. EDZ is permeable fractured rock formed by blasting [11].

Designers of underground repositories have to predict the rate of percolation of groundwater through the waste-bearing part of the repository and to find the rate and annual amount of radionuclides brought with the water to the environment. A first and most important matter in doing so is to 1) identify and define the structure of the rock, 2) find relevant values of the hydraulic gradient and conductivity of the various zones that make up the host rock, and 3) calculate the transport of radionuclides. While the hydraulic gradient can be up to 10 m/m or temporarily even higher for a top liner, it is less than 0.1m/m for liners in a fully water saturated underground repository.

3.3.2 Stability and hydraulic performance of host rock

For relatively shallow underground repositories rock stability issues are similar to those met with in the mining industry and in construction for infrastructural purposes like railway and road tunnels. Designers have to be acquainted with modern rock stability technology according to which one needs to base calculations of rock stability on the orientation and magnitude of the site-specific principal rock stresses, and on the crack initiation stress, which commonly ranges between 80 and 140MPa averaging at 100-120MPa for good crystalline rock. For construction of larger and deeper tunnels and rooms in which the performance of bigger rock volumes is involved, the rock structure plays a very important role. This is illustrated by the cross section of a cavern with 30m diameter and 65m height prepared by blasting for hosting a concrete silo for some 7,000 tons of LLW/ILW in operation some 100 kilometers north of Stockholm in Sweden. The waste is contained in concrete boxes stacked in vertical cells and in tunnels (Figures 9 and 10), where such boxes are placed and surrounded by backfill with appreciable gas conductivity [19]. The filling of granular montmorillonite-rich clay material for isolating the silo from the rock was made by use of a hopper moved along the periphery at the upper end of the silo. This gave uniform distribution of the clay material and a dry bulk density of 1,100 to 1,200kg/m^3 (Figure 11). This indicated that compression of the fill in the placement phase under its own weight was insignificant and careful measurement of the compression in the following five years showed neither compression nor expansion despite the wetting that had taken place by diffusive migration of moisture from the rock, which had been kept drained [20]. It should be underlined that abandoned mines may well be used for disposal of radioactive waste according to the principle shown in Figure 8 [20].

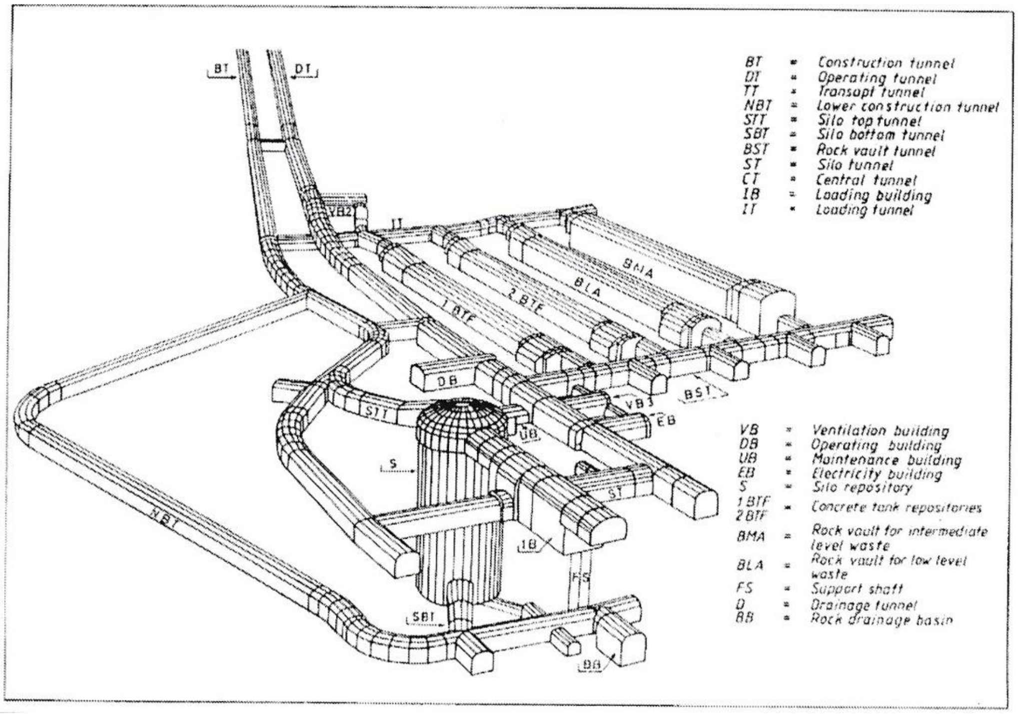

Figure 9: Overview of SKB's facility for disposal of LLW in tunnels and of LLW and ILW in a concrete silo built in a big cavern (After SKB).

1) Transport tunnel, 2) Cells, 3) Elevator, 4) Waste packages, 5) Protection against dripping water in the waste placement phase, 6) Silo cover of porous concrete or cement-stabilized quartz sand, 7) Filling of smectite clay granules, 8) Bottom bed of strongly compacted mixture of 10 % clay granules and graded sand/gravel, 9) shotcrete, 10) Drains, 11) Tunnel for discharge of drain-water until the repository is closed

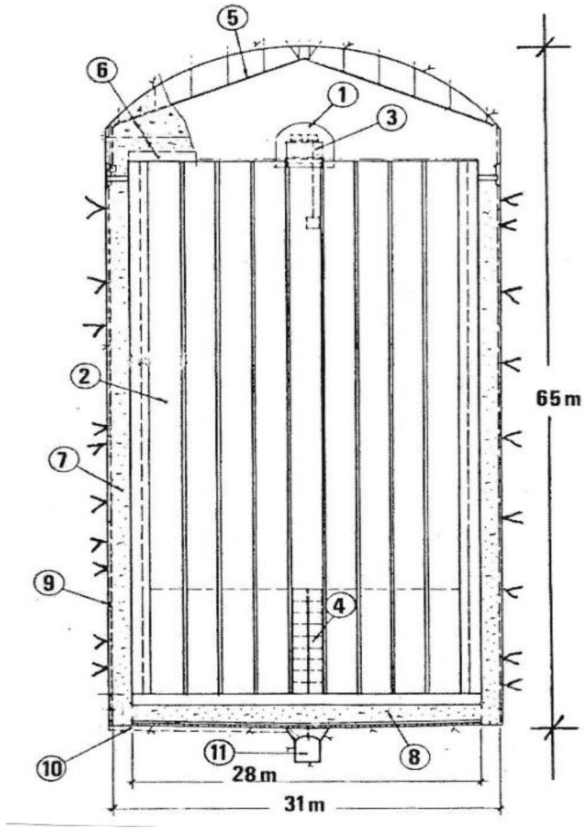

Figure 10: The disposal facility at Forsmark, Sweden showing the big silo for disposal of LLW and ILW and the system of tunnels for storage of very low-active radioactive waste (After SKB).

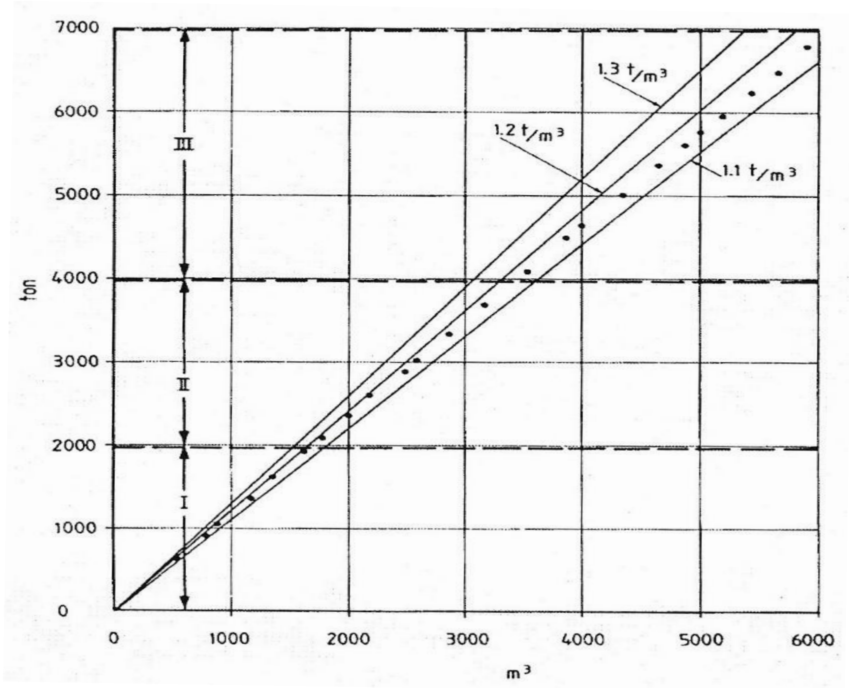

Figure 11: Bulk density of the granulated clay fill determined in the course of the placement made by use of a hopper located about 50 m over filled mass (left). The density is expressed in tons per cubic meter in the graph [19,20].

4. Location of repositories for LLW and ILW

We have mentioned some criteria related to design and construction of repositories on-ground on rock and underground in crystalline rock. On a larger scale rules for selection of sites for disposal of LLW and ILW are set by national authorities after evaluation of their suitability from viewpoints like presence of precious raw material, such as oil, gas and certain metal ore, and restrictions caused by infrastructural conditions. Using general experience and building codes the overall topographic and hydrological criteria should be (cf [10]):

- The general flow direction of the groundwater should be downstream communities for minimal contamination of the ground in populated areas. Climatic changes and various large-scale construction projects can alter the hydrologic pattern including the flow direction of both shallow water and groundwater,
- Selection of a site on the floodplain of a major river (like Indus, river Rhein in Germany, Mississippi in the US and Tigris and Euphrate in Iraq) requires location well over the level representing 100-year flooding. Positions very near rivers and lakes with controlled water table for irrigation and hydropower utilization should be avoided,

- A site with deep groundwater level in a long-term perspective is desired,
- Wetlands, marshes, fenlands and bogs, which occupy large parts of northern Canada, Russia and Scandinavia should be avoided since organic soil is strongly compressible and causes large settlement of vaults and drainages [2,10,11]. pH of soils in such areas is usually very low and can cause rapid corrosion of waste containers and disintegration and dissolution of clay and concrete seals.

Plans to locate on-ground repositories requires that the underground, soil or rock, is low-compressible like bottom moraine, and characterized through sufficiently comprehensive geotechnical explorations. The topography and stratigraphy often vary as exemplified by the common complex conditions in areas that have undergone glaciation like Canada, Scandinavia, Russia, and Korea (cf. Figure 12). Microstructural variations have to be considered where the piezometric conditions and hence the local stability are controlled by the porewater pressure, as in sloping terrain (Figure 13).

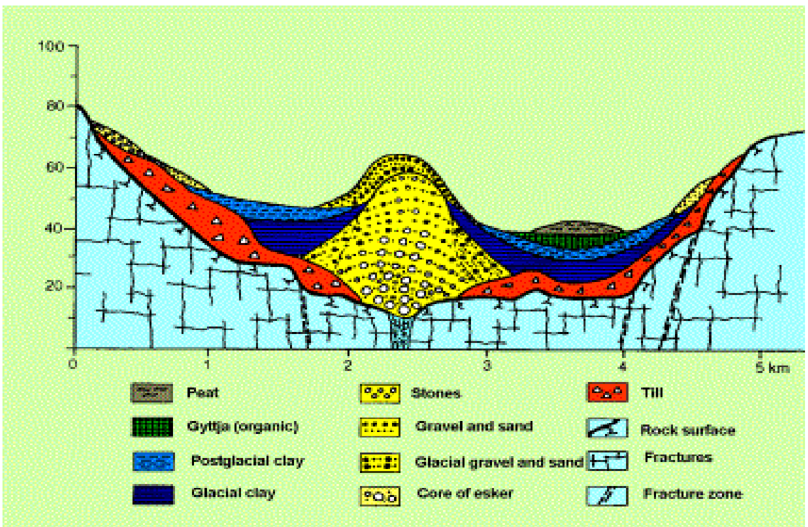

Figure 12: Example of macroscopic heterogeneity: Cross section of present major rivers in Scandinavia (After Swedish Geological Survey).

Since vertical percolation of an on-ground repository can bring radionuclides down into the underground groundwater and further to recipients, fracture zones can serve as transport paths. This makes it necessary to run site investigations so that they can be identified and avoided in localizing repositories (Figures 13a and b).

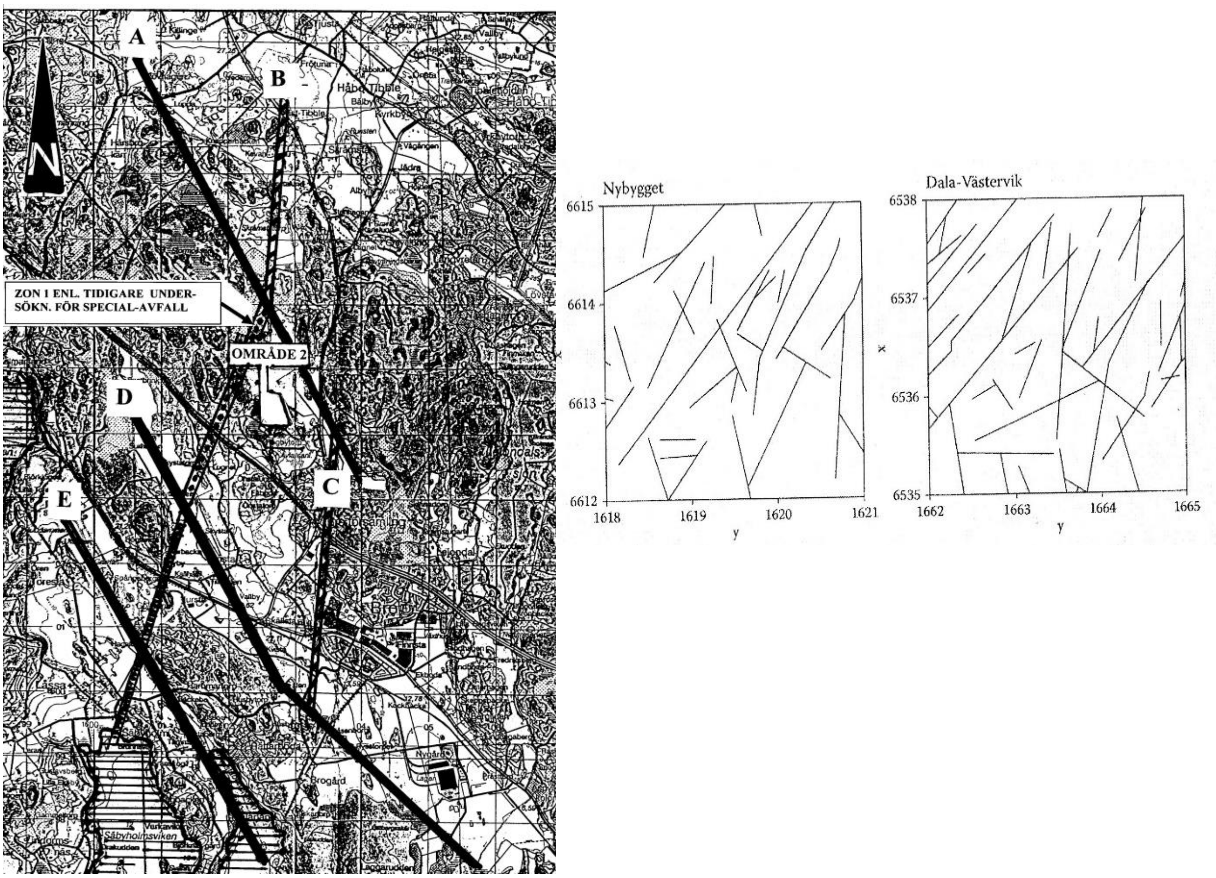

Figure 13: Fracture zones in granite identified by geologic and topographic site selection analyses. a) Common pattern of fracture zones (edge length 0.7x1.1 km). b) large-scale patterns of major fracture zones in granite (left) and in gneiss (Scale in kilometers).

Underground disposal of LLW and ILW in vaults requires that the same factors be considered in the site selection process as for on-ground disposal, the most important ones being *socio/economic issues* including use of groundwater resources, and the *properties of the disposal site and its neighbouring environment.* The first mentioned are exactly the same as for on-ground disposal while the physical constitution and properties of the sites can be quite different.

The International Atomic Energy Agency (IAEA), acting as a global inspectorate for the production of nuclear energy and disposal of radioactive waste, has documented international work on geological disposal since the 1950s, when deep salt formations were considered for disposal of LLW and ILW in the US. Since we are focusing on artificial barriers, primarily clay materials, to radionuclide transport we will not discuss disposal of such wastes in salt rock here but refer the interested reader to relevant literature [2]. Likewise, we refrain from considering clastic clay, like the Boom clay sediments in Belgium, since there are very few concepts of its kind, and since there are considerable uncertainties concerning the involved physical/chemical long-term processes (consolidation, creep strain, and cementation).

For both on-ground and underground disposal of LLW and ILW major structural weaknesses in the rock upon or within which disposal is considered, have to be investigated. This is primarily for getting indications of possible instability in the construction phase and for identifying geologic features that represent present and future groundwater flow paths and weaknesses along which seismically and tectonically induced displacements can take place, as exemplified by the weathered zone in Figure 14, and by crossings of water-bearing fractures like those in Figure 15.

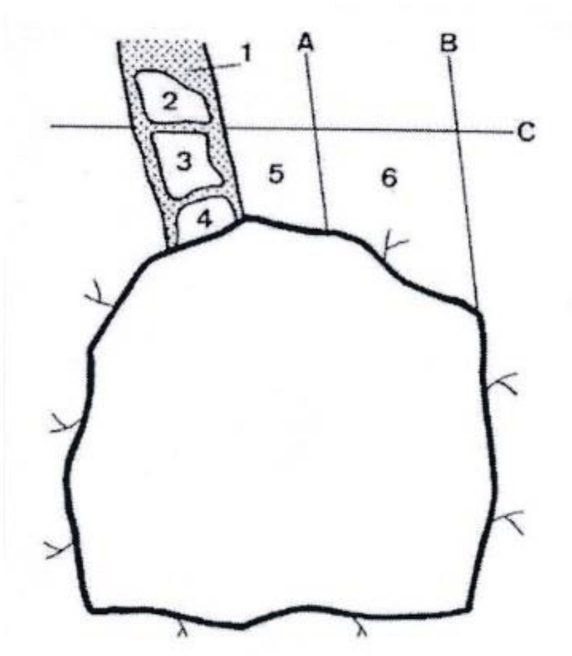

Figure 14: Tunnel section with seams of clay-weathered crystalline rock and potentially unstable rock blocks (1-4). A-C are fractures with insignificant or no gouge but with a potential to weaken by weathering.

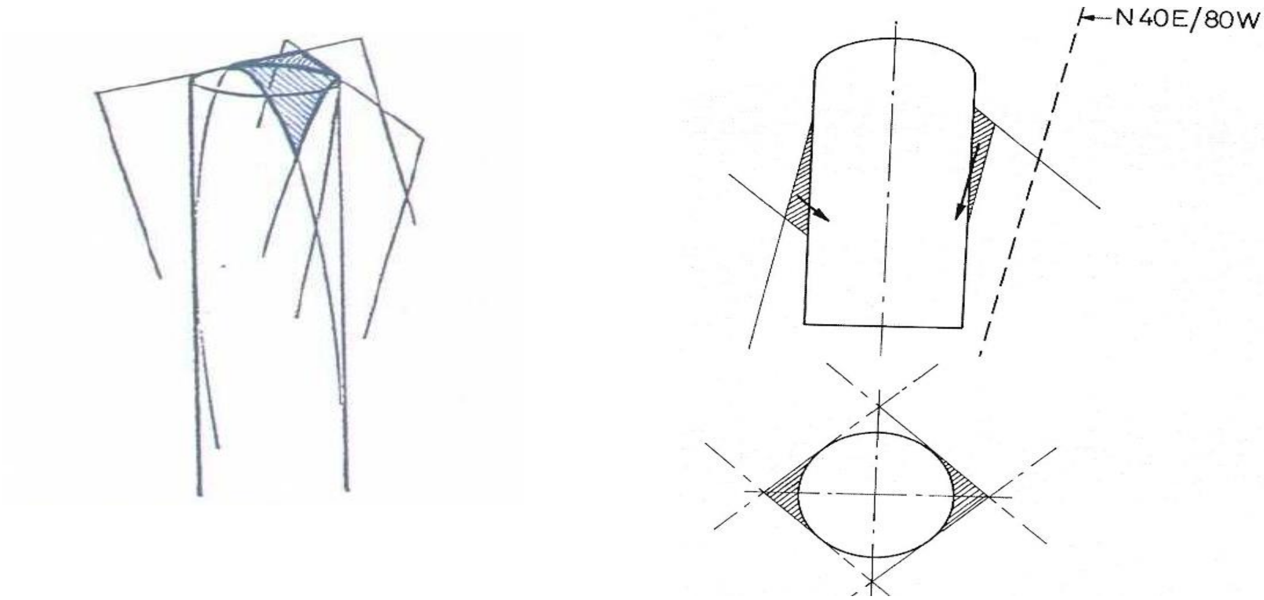

Figure 15: Unstable rock wedges formed by crossings of steeply oriented fracture zones or discrete fractures. The right picture refers to the room hosting the big silo in Figure 10. The crossings are major hydraulic conductors.

5. Function of LLW and ILW isolation

5.1 Clay Barriers

Clay minerals belonging to the smectite family, of which montmorillonite is the most common member, represent materials for shielding and containment of radioactive waste. The physical and chemical performances in bulk are manifested by the interactions of the microstructural units that make up the macroscopic skeletal network of the clay. The mechanical and physico-chemical properties of a clay soil depend on the degree of homogeneity of the microstructural constitution and on the reactions between microstructural units and porewater. The properties and interactions of interest, such as hydraulic conductivity, gas penetrability, ion diffusivity, shear strength, creep potential, and erodibility are those to be considered. Our interest focuses on the finding and practical use of relationships between the microstructural constitution of clays and practically important material properties in bulk [11].

5.1.1 Migration of contaminated water

The hydraulic conductivity of smectitic clay depends to a very large extent on the size and interconnectivity of the voids and on the variation in density. The presence and spatial distribution of low-density zones on micro- and macroscopic scales are critical factors, since they control the volume of flow that can take place. Most of them are extremely small in smectite microstructure and have limited continuity. For low and medium densities, and particularly when the dominant exchangeable cations are Ca, the hydraulic conductivity is measurably increased due to the development of channels. The viscous hydration water (nH_2O) within the interlamellar space (Figure16 left pair), and the more or less stagnant water in the large number of very narrow pores of the microstructure (right in the figure), constitute water that has very low mobility. Water has normal fluidity in the macropores and other wider void spaces where it has properties that are similar to those of bulk water.

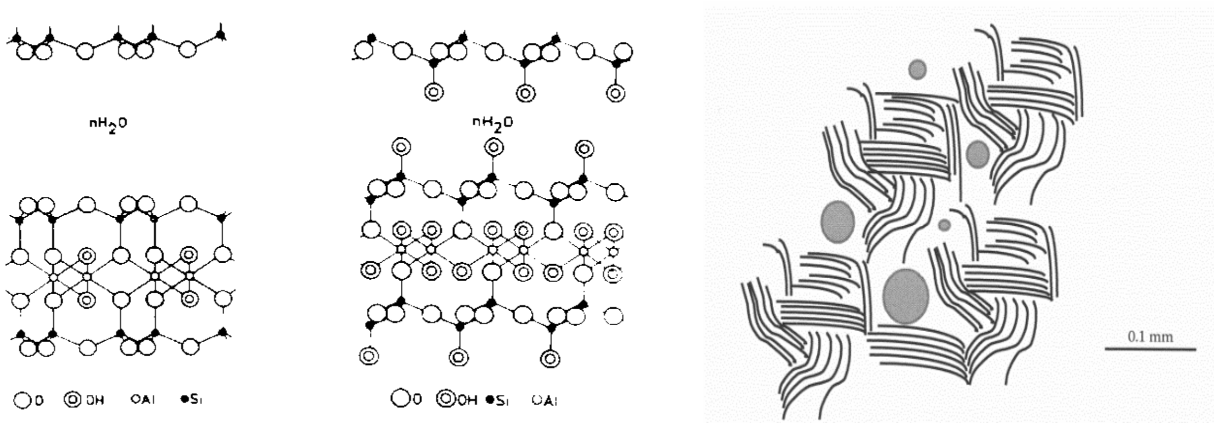

Figure 16: The smectite mineral montmorillonite. Left: Crystal structure models with interlamellar water. Right: Schematic microstructural model of hydrated clay with bulk density 1,800-2,000kg/m^3 at water saturation. For the lower density the bar is 0.1 mm and for the higher it is 0.01mm. Circles are channels with water and dilute clay gels [11].

The bulk hydraulic conductivity is determined by percolating a confined sample of clay and measuring the amount of water Q passing through it per time unit under a known hydraulic gradient i. Darcy's model is used for evaluation of the conductivity and since the cross-sectional area A of the sample is known, the average hydraulic conductivity K is $v= Q/A = Ki$. The gradient should not be higher than 100 m/m (meter water head per meter flow length) for avoiding internal erosion and clogging [11]. The role of soil microstructure can be specified in terms of the matric and osmotic potentials. For any clay type an increase in density will result in a reduction of the number of larger voids and an increase in microstructural homogeneity by tighter packing of individual particles and particle aggregates. For smectite clay this is demonstrated by the data in Table 1.

Table 1: Typical hydraulic conductivity (*K*) versus density of montmorillonitic clay [11].

Montmorillonite Content, %	Bulk dry Density [kg/m^3]	*K* [m/s] for saturation and percolation with distilled water	*K* [m/s] for saturation and percolation with 3.5 % $CaCl_2$ solution
10	2,180	2E-11	5E-11
10	1,970	9E-10	2E-11
10	1,750	E-09	5E-09
20	1,880	E-11	5E-11
20	1,750	5E-11	E-10
20	1,200	E-10	E-09
>60	1,750	E-13	5E-13
>60	1,550	E-11	E-12
>60	1,430	E-10	5E-12
>60	1,270	1.2E-09	5E-11

The table shows that clay with a content of smectite as low as 20% can have the low bulk hydraulic conductivity E-11m/s that is required by certain national regulators, provided that the dry density is at least 1,900kg/m^3. This density can be obtained for sloping clay liners by several runs of vibratory pad-foot rollers or plates [1]. For clay seals that may become percolated by salt solutions, like bottom liners and top liners of on-ground repositories in coastal areas, the conductivity can be 5 to 10 times higher. This effect, which is caused by coagulation of the particle network, is particularly strong for low densities: particle aggregates in the channels shrink leaving larger voids between them (Figure 17).

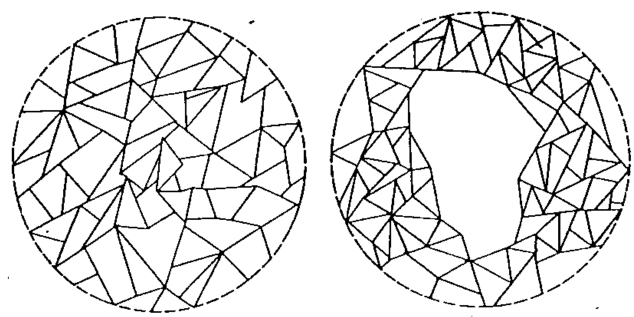

Figure 17: Coagulation of clay particles. Left: Structurally homogeneous clay network. Right: Coagulation by increased electrolyte concentration in the porewater.

5.1.2 Diffusive transport of radionuclides

Ion diffusion in and through clay liners and other clay seals is important where water is stagnant. The factors controlling the transport of contaminant ions are: (a) type and activity of clay constituents, (b) cation exchange capacity (CEC) and their specific surface area (SSA), (c) chemistry of the porewater, (d) species and concentration of the contaminant radionuclides, (e) redox potential and pH, and (f) kinds of soil micro-organisms in the system.

The diffusion transport capacity expressed by the ”effective” diffusion coefficient D_e refers to the actual ”effective” porosity, i.e. the integrated geometrically defined void system with due respect to retardation by mineral surface forces, and describes ion transport on the microstructural level. This is in contrast to the ”apparent” diffusion coefficient, which is a general measure of diffusion directly evaluated from recorded concentration profiles. Cation diffusion takes place in several ways, i.e. in continuous water-filled voids, along particle surfaces with electrical double-layers, and through the interlamellar space in smectites (Figure 18). The latter two mechanisms involve ion-exchange mechanisms, of which the sorption parameter, K_d, is a measure. The density of the clay plays an important role as illustrated by Figure 18.

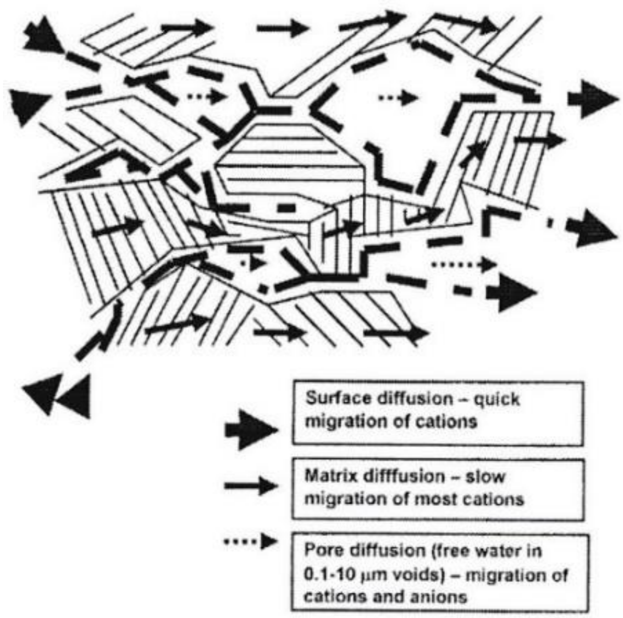

Figure 18: Smectite clay microstructure with dense particle aggregates shown as hatched areas. Surface diffusion takes place along the exposed free surface of aggregates of stacks of smectite lamellae. Matrix diffusion occurs within the aggregates, primarily by cation diffusion in the interlamellar space, while pore diffusion takes place in wider voids.

Simplifying the matter a bit one can describe diffusive cation transport as taking place by surface diffusion in the electrical double-layers, by “matrix diffusion”, implying ion transport in the interlamellar space, and by pore diffusion taking place in free porewater, i.e. at more than about 3 water molecules distance from the mineral surfaces [11,21]. The diffusive anion transport capacity is proportional to the ratio of the pore space of the voids between the stacks of smectite lamellae. Anions are excluded from the interlamellar void space by the Donnan effect. With increasing clay density, the available space for migration is reduced, and the diffusion coefficient of anions therefore drops significantly (Figure 19). Since many cations move both by pore diffusion and surface diffusion, the retarding effect resulting from increased densities on the diffusion capacity of cations is limited for monovalent ions.

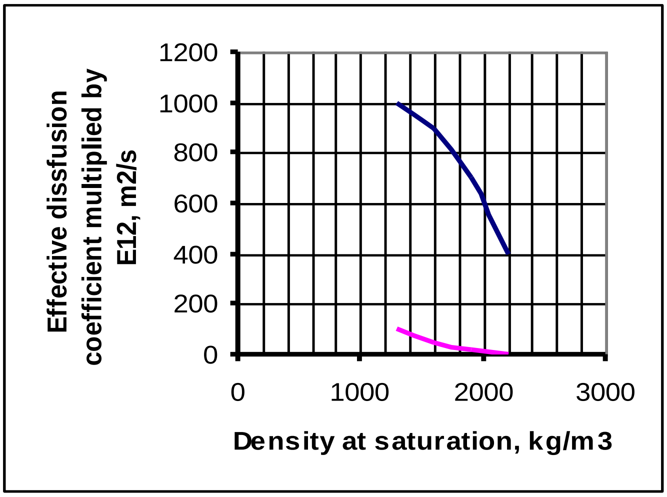

Figure 19: Measured effective diffusivities of smectite clay. The upper curve refers to monovalent cations and the lower to anions.

5.1.3 Erosion and erodibility

High flow rates can cause local erosion of fully water-saturated smectite clay. The perspectives from physical models and experiments show that the critical rates for tearing off smectite particles and particle aggregates from the surface of clay exposed to flow parallel to it as in microstructural channels are illustrated by Table 2 and Figure 20.

Table 2: Critical water flow rate in channels in montmorillonite-rich clay for generating erosion [22].

Diameter of eroded particles and stacks of particles [μm]	Critical flow rate, [m/s]
0.5	E-3
1.0	E-4
10.0	E-5
20.0	E-7

Piping in the form of a hydraulic wedge penetrating into soft smectite clay matrix. 20-50 μm aggregates are moved by the flow (E-4m/s). Notice the "meandering" process of erosion [22].

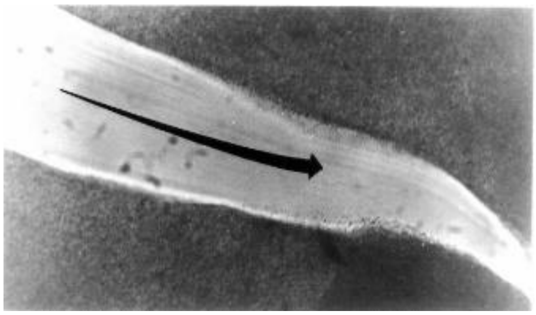

Figure 20: Erosion of smectite clay.

In design of repositories for LLW and ILW as well as High-Level Radioactive Waste (HLW) one needs to consider the impact of gas (water vapour, carbon dioxide, hydrogen, methane) generation on the integrity of the waste-isolation facility. The matter has been frequently discussed in the literature, especially for LLW/ILW repositories of the type shown in Figures 3 and 4, focusing on practical ways of letting high gas pressure dissipate in a controlled fashion. A possible solution of the problem is to install porous ceramic filters for discharge of gas from a sand layer below the concrete top of the vaults. Without such arrangements the gas pressure can be high enough to break the concrete, and in clay liners and fills that are not confined in concrete vaults or rooms, the clay can be destroyed by being transformed to "mud volcanoes" [23].

A channel in smectitic clay caused by penetrating gas can self-heal by the expandability of the clay. This is required for keeping clay layers in gas- and oilfields tight, which is reported to require a porosity lower than 30 % and a Na/Ca ratio of at least 4, and microstructural homogeneity of the clay. For very dense smectitic clays the critical gas pressure is on the same order of magnitude as the bulk swelling pressure, as affirmed by the results shown in Table 3.

Table 3: Experimentally determined critical gas pressure [MPa] for dense, smectite-rich clay [24].

Density at saturation, [kg/m^3]	Experimentally determined critical gas pressure, [MPa]	Swelling pressure of dense smectite-rich clay matrix, [MPa]
2,130	20	20
1,850	2	1
1,570	0.1	0.2

5.2 Chemical and mineralogical stability

5.2.1 General

The demand for long-term barrier function of clay liners and fillings of smectite soils in LLW/ILW repositories is less than for HLW since the half-life time is much shorter and there is almost no heat production. Still, low- and intermediate-level wastes need to be isolated from man, cattle and pets, and also from food, which requires effective shielding and protection by confinement exemplified in this paper. As concerns the minerals in clay-based barriers, several laboratory investigations and examples of geologic evidence have shown that the smectitic minerals provide the required isolation capacity from radioactivity. The only degradation process that one can expect is some minor conversion from the initial state of dominant smectite to a reduction in smectite content and a corresponding increase in non-expanding minerals like illite and chlorite by a few percent in a 1,000-year perspective. Still, one has to keep in mind certain changes in on-ground repositories in deserts, where the temperature can reach over 70^{o}C and cause release of potassium from sandy erosion-protective top layers, thereby enhancing conversion of smectite to non-expandable and amorphous forms. This can also lead to cementation by precipitation of silica and iron compounds, which would reduce the self-sealing potential of the clay liners [11].

5.2.2 Mineralogical processes

Mineralogical changes in montmorillonite have been extensively treated in the literature with focus on the influence of temperature and porewater chemistry [25,26,27,28]. Specific studies on the impact on the physical performance of smectite clays, especially the mechanical strength, have been conducted in later time. Here, we will refer to the conversion model proposed by Grindrod and Takase [25], which has been used for quantifying dissolution and precipitation of phyllosilicates and silica by taking $O_{10}(OH)_2$ as a basic unit. It defines a general formula for smectite (S) and illite (I) as:

$$X_{0.35}\,Mg_{0.33}\,Al_{1.65}\,Si_4O_{10}\,(OH)_2 \text{ and } K_{0.5\text{-}0.75}\,Al_{2.5\text{-}2.75}\,Si_{3.25\text{-}3.5}\,O_{10}(OH)_2 \qquad (2)$$

where X is the interlamellar absorbed cation (Na) for Na montmorillonite, or (Ca) for Ca montmorillonite etc.

According to this model the rate of the reaction *r* can be expressed as:

$$r = A \exp(-E_a/RT)(K^+)S^2 \quad (3)$$

where: A=coefficient, E_a=activation energy for the conversion of montmorillonite to illite, R=universal gas constant, T=absolute temperature, K^+=potassium concentration in the porewater, and S=specific surface area.

One finds that there will be almost no mineralogical changes in smectite-rich clay for temperatures lower than about 60°C for geologic periods as long as pH ranges between about 6 and 10. This exception is very important since the porewater of concrete based on Portland cement has pH 12-13 and hence attacks smectites very severely, [29,30]. Montmorillonite, being the number one smectite candidate, is converted to (non-expansive) illite via mixed-layer smectite/illite minerals or precipitated as such, and to quartz, cristobalite and amorphous silicates as illustrated in Figure 21. These reaction products are formed at a rate determined by temperature and access to potassium as illustrated in the Figure, [21]. For LLW/ILW repositories on-ground, conversion of this very common member of the smectite family will be insignificant except where it is in contact with concrete. Here, degradation of both will take place causing cation exchange to calcium in the clay and dissolution and loss of $Ca(OH)_2$ ("portlandite") in the concrete. Since portlandite forms coatings of ballast particles, loss of it causes reduction in strength of the concrete, while the hydraulic conductivity will go down with time because of channel-clogging precipitates. For the smectite clay in LLW/ILW repositories the indications of mineral preservation are very strong [20,27]. For smectites in contact with concrete based on Portland cement there is, however, clear indication of significant mutual dissolution and secondary precipitation of minerals or gel complexes that cause cementation. This leads to loss of ductility and ability to self-heal, and to reduction in hydraulic conductivity.

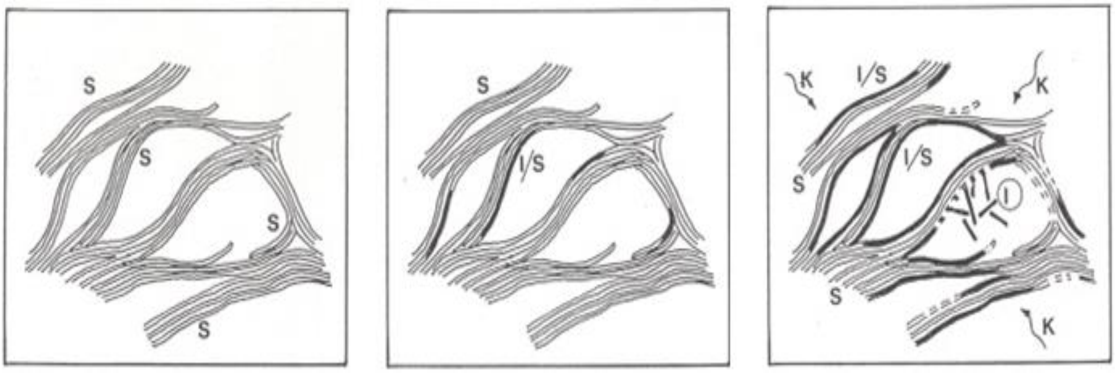

Figure 21: Smectite-to-illite conversion via mixed-layer I/S formation and/or direct precipitation of illite. Dark contours represent precipitations of silica and/or illite. S is smectite, I is Illite, and K is potassium [21].

5.2.3 Smectite/concrete reactions

The most important threat to clay seals in LLW/ILW repositories is the chemical reaction of smectite clay and concrete that will be abundant in both on-ground repositories with waste stored in vaults, and in underground repositories. Basic to this issue is the conclusion from the international Stripa Project [19,20] that the high pH level in concrete porewater, particularly in the (Portland) cement phase, can degrade contacting smectite clay. The process has been modelled as a matter of dissolution and diffusive transport of released calcium into contacting montmorillonite-rich clay. A less reactive, promising alternative concrete composed according to Table 4 has been successfully tested [29,30]. The components were 1) low-pH cement, 2) quartzite aggregate and 3) talc as superplasticizer. Experimental work in the form of hydrothermal treatment of such concretes with 6-8 % cement at temperatures relevant to both LLW/ILW and HLW repositories, i.e. up to 150^{o}C, has been made. Samples of such concrete in contact with montmorillonite-rich clay were treated and tested in the same way leading to the conclusion that neither of the two components underwent significant changes in mineral contents and physical performance. The long-term compressive strength of either of them was in fact higher than for concrete with Portland cement.

Table 4: Talc (T) concrete recipe for Merit 5000 cement.

Cement/ aggregate ratio	Water/ cement ratio	Cement weight [%]	Talc weight [%]	Aggregate weight [%]	Water weight [%]	Density [kg/m^3]
0.078	3.6	0.8	7.6	68.0	23.6	2028

The cement content (0.8 %) was taken to be very low in order to limit the growth in void size that results from dissolution and loss of it, and also for minimizing the impact of high pH on the chemical stability of contacting clay seals. The density of the concrete is believed to be sufficiently high to make the concrete perform acceptably for very long periods of time even after complete loss of the cement since the aggregate matrix is as stiff as moraine soil. pH of the Merit concrete is around 10 and hence considerably lower than that of Portland concrete. The hydraulic conductivity of matured talc concrete is E-10 m/s, i.e. of the same order as that of the clay liners with 0.5-1 m thickness in on-ground and underground repositories, like the silo construction described in Section 2.

6. Comments and conclusions

While the amount of highly radioactive waste to be disposed of globally is relatively small over time, that of low- and intermediate-level waste can be very large and disposal of this worthless material can therefore be very demanding, both respecting the required space on-ground or underground and the risk of environmental contamination by natural processes and terrorism. Simple and cheap concepts and methods for construction are required and those already in use and mentioned in the paper are guiding examples. In the authors' minds disposal underground appears to be superior to on-ground disposal, especially respecting the risk of terror actions and conversion of deep mines to repositories seems particularly attractive. Risk of seismic, tectonic and meteoric impact and associated damage to on-ground facilities also speak in favour of underground disposal.

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