Geologic Disposal of High-Level Radioactive Waste—Status, Key Issues, and Trends

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Abstract:

The permanent disposal of high-level radioactive waste is one of the major technical hurdles that must be addressed if electrical power production by nuclear energy is to remain viable. The main challenge is that the waste must be effectively isolated from interactions with the biosphere for hundreds of thousands of years. A number of permanent disposal options have been proposed and reviewed by various countries and scientific organizations during the past few decades, and there appears to be a consensus today that mined geologic disposal is the most practical and effective method. Several variations on mined geologic disposal are being intensively studied by waste-producing countries. These investigations address a wide range of scientific questions, such as the behavior of geological and engineered barriers over time, or the use of quantitative modeling and qualitative observational evidence to demonstrate the safety of disposal. The present paper provides an overview of current approaches, scientific issues, and safety assessments related to mined geologic repositories for high-level radioactive waste.

Outline:

Key Words for Indexing:

Barriers, Isolation, Repository, Safety

Glossary:

Engineered barriers are the engineered part of the disposal system, primarily consisting of the waste form, waste package, backfill, ground support, excavated openings of the repository, and any seals and plugs used to close such openings.

Natural barriers are formed by the rock formations around the repository and along the radionuclide transport pathways that affect the movement of fluid, colloids, dissolved constituents, heat, and transmission of mechanical stress.

Biosphere is the part of the earth and atmosphere where living organisms exist.

High-level radioactive waste is spent fuel or spent fuel reprocessing waste that has high levels of radioactivity and generates significant quantities of heat.

Spent nuclear fuel is fuel that has been irradiated in a nuclear reactor to the point that the build-up of fission products and transuranics interferes with the fission reaction. As a result, it is removed from the reactor and replaced with fresh fuel to maintain the reactor's energy output.

Once-through fuel cycle is where spent fuel is disposed of directly as high-level waste.

Reprocessing is the separation of spent fuel into components that can be returned as fuel to the nuclear reactor and components that are waste.

Acronyms:

CFM:	colloid formation and migration
EDZ:	excavation damaged zone
ESF:	Exploratory Studies Facility
FEBEX:	Full-scale Engineered Barriers Experiment
FEPs:	features, events, and processes
HADES:	High Activity Disposal Experimental Site
THM:	thermal-hydro-mechanical
URL:	underground research laboratory

1 Introduction

The future of nuclear power is confronted with several challenges, such as societal concerns about catastrophic accidents (particularly after the disaster at Fukishima Daiichi) or economic realities related to the high cost of nuclear installations. But perhaps the issue that has over the last decades triggered the greatest and most consistent public concern is the high-level radioactive waste generated by nuclear power plants and other nuclear installations (1). The overarching complication of radioactive waste management is the long-lived toxicity of the waste, which requires isolating it from the biosphere for many hundreds of thousands of years. An international consensus has emerged that such isolation can best be provided by disposal of the waste in geologic repositories, a strategy that today is pursued by most countries in possession of nuclear waste. It is now widely accepted among experts from national waste-management organizations and related international bodies—such as the International Atomic Energy Agency (IAEA) or the Nuclear Energy Agency (NEA) —that the burial of high-level radioactive waste in mined geologic repositories is technically feasible, and that it can provide adequate protection to humans and the environment.

This assessment is not necessarily shared, however, by all stakeholders, and issues related to public distrust, inconsistent policies, or political changes have challenged or disrupted disposal programs in several nations (2)—such as Canada, the United Kingdom, Germany, and, most recently, the United States—and no high-level waste disposal facilities are yet in operation anywhere in the world. Some other nuclear nations, on the other hand, are moving forward as scheduled with their site selection and site approval process. According to current plans, Finland, Sweden, and France are expecting the start of geologic repository operations in the 2020–2025 time frame (2).

While the disposal of nuclear waste continues to face technical, social and political difficulties, existing and emerging nuclear nations do not have the luxury of simply ignoring the issue. Substantial amounts of high-level waste already exist, and more are being produced. Transmuting waste in reactors or accelerators could theoretically reduce waste volumes, but never completely, and the technology for advanced transmutation still needs to overcome considerable challenges. Surface storage of high-level waste can provide a temporary relief, but has its own environmental (and other) risks, and is certainly no long-term option. At this time, there is no realistic alternative to long-term waste isolation via geologic disposal.

This article reviews some of the key questions related to disposal of high-level waste in mined geologic repositories, from a technical and scientific perspective. It starts with an overview of the nuclear waste disposal problem, including current waste inventory, waste types, alternative disposal options, and management/institutional issues, followed by a basic description of the waste isolation capability of mined geologic repositories and their multiple barrier functions. The article then gives a technical discussion of the physical and chemical processes affecting the long-term performance of a mined geologic repository, and describes how these processes are being studied in underground research laboratories (URLs). The final section presents issues associated with demonstrating safety via qualitative and quantitative assessment of disposal system performance and the necessity of appropriately accounting for uncertainty.

2 Background

High-level radioactive waste is mainly associated with the generation of nuclear power and, to a lesser extent, the production of nuclear weapons. With regards to power generation, the high-level waste is either comprised of spent nuclear fuel or constitutes the radioactive material remaining after reprocessing of spent fuel (http://www.nrc.gov/waste/high-level-waste.html). High-level waste is characterized by high levels of radioactivity and the generation of significant quantities of heat due to decay. Low- and intermediate-level radioactive waste is considered to be less hazardous and is typically disposed of separately (http://www.oecd-nea.org/brief/brief-06.html) (3). A separate category used in the United States, transuranic waste, is waste that contains long-lived transuranic radionuclides but does not generate significant quantities of heat. There is an operating permanent disposal facility for transuranic waste, the Waste Isolation Pilot Plant, near Carlsbad, New Mexico. This mined geologic disposal facility is constructed in a bedded salt formation at a depth of about 650 m (4, 5).

2.1 Radioactive Waste Inventory and Nuclear Fuel Cycles

The current inventory of high-level waste may be summarized in terms of the radioactivity measured in curies (Ci), where 1 Ci is 3.7×10^{10} becquerels or decays per second. The total amount of commercial spent (or used) fuel worldwide is about 7.6×10^{11} Ci, while the amount of reprocessed waste is about 2.0×10^{9} Ci (6). From these rough estimates, it is clear that most of the radioactivity (>99%) is in the spent fuel. The quantities of spent fuel are not evenly divided among the waste-producing countries. About 60% of the total inventory of spent fuel is found in just three countries, 29% in the United States, 20% in Canada, and 11% in Russia, and 91% of the existing spent fuel is from ten countries. The worldwide inventory of spent fuel is about 180,000 metric tons of heavy metal (as of 2005) and additional waste is being generated at a rate of about 10,000 metric tons of heavy metal per year (6).

The radioactivity of spent fuel is highest at the point it leaves the reactor or the nuclear facility. There are many short-lived radionuclides that decay rapidly, initially causing the radioactivity to decrease fast. Successively longer-lived radionuclides dominate the total radioactivity as the waste ages outside the reactor. Figure 2.1 shows that the radioactivity level of the spent fuel is mainly caused by fission products for the first few hundred years, but is then dominated by actinides at longer times (7). A similar pattern is found for thermal energy release in terms of heat generation being dominated at early times by fission product decay and at later times by actinides (8).

Different fuel cycles result in different treatments for spent fuel. For the "once-through" fuel cycle (i.e., without reprocessing of waste), nuclear power facilities store the spent fuel on site in spent fuel pools immediately after removal and often transfer them to dry cask storage after about 5 years of cool-down (http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/dry-cask-storage.html). The waste is expected to remain in such interim storage for several decades, covering the period of highest toxicity and heat generation, before placement into a permanent disposal facility is envisioned. While disposal will always be needed at some point in the future, the concept of extended storage for durations of 60 to more than 100 years has been suggested as an alternative to developing permanent disposal systems in the near term. Additional R&D would be required to investigate the feasibility and safety of extended storage beyond 60 years of disposal system lifetime (9).

Alternatives to the once-through cycle involve some type of reprocessing of spent nuclear fuel (10). The only alternative currently used commercially is the modified-open cycle using mixed-oxide fuel. More advanced fuel cycles have been proposed, but need to overcome technical and economical challenges, and are decades away from commercial implementation. In theory, these fuel cycles could significantly reduce the volume of high-level waste and could eliminate certain actinides in the waste, but the need for long-term waste disposal would still remain (10).

2.2 Alternative Geologic Disposal Options

A wide variety of long-term disposal options have been considered over the past decades, including methods that are not related to geologic disposal, e.g., shooting the waste into space (11), but most of these have been dismissed based on safety concerns, cost, or other fundamental problems. The only options considered potentially viable today are all based on geologic disposal. Of these geologic disposal options, recent evaluations (or re-evaluations) by various countries and international organizations continue to support mined geologic disposal as the most practical and effective method for permanent disposal of high-level waste (10, 11, 12, 13). Basic design and safety considerations for mined geologic repositories are described in Section 3.

The closest alternative to mined geologic disposal is to place the waste into boreholes of up to 5 km depth. Recent expert reviews found deep borehole disposal to be technically promising (10, 11), but also recognized that the concept has not been investigated as thoroughly as mined geologic disposal, and requires further research and development. Other geologic disposal options that have been discussed in the past, such as placement of waste on or within the ice sheet in Antarctica (14), subseabed disposal, and burial beneath islands (10, 11, 12, 15). These latter alternatives have not been pursued, mainly because of difficulties concerning international policies and treaties, opposition from environmental organizations, and public acceptance issues.

2.3 Governance and Management

Institutional processes are important in the development of high-level waste disposal systems. Given the natural tendency for the societal cost and impact of any waste to fall outside the purview of normal market economic forces, governance is needed to bring these costs and impacts into balance. Governance for radioactive waste is generally implemented through a governmental regulatory process, which has been followed by all countries faced with high-level radioactive waste disposal issues (16). Some differences among nuclear nations exist and are mainly in the details of how the regulations have been written, in terms of what levels of dose and risk rates, as well as the time frame of the regulations (Section 5.1).

The implementing organizations tasked with management of nuclear waste disposal around the world are more diverse than regulatory bodies. Generally speaking, the implementing organizations fall into one of four categories: government agencies, private corporations, government-owned corporations, and public-private partnerships (16). Implementing organizations are faced with an array of difficult issues: (a) complex technical issues that carry large degrees of uncertainty and significant short and long-term risks; (b) a high degree of political and public controversy that makes for difficult relationships with stakeholders; and (c) difficulty in maintaining stable financing and resource support, political legitimacy, and structural integrity over the time required to develop a permanent disposal system (likely to be close to 100 years) (17). To address these issues, management organizations are advised to (a) implement a decentralized authority structure; (b) openly acknowledge uncertainties; (c) proactively interact with affected localities, institutions, and the public; and (d) ensure that funding is segregated from general government revenues (2, 17). Part of the management challenge is to retain public confidence during the inevitably long process of site selection, site characterization, and repository development. A major step toward achieving such confidence may be through consensus-based approaches, which have been successful in Finland and Sweden (10).

3 Mined Geologic Disposal

In a mined geologic disposal system, waste is placed in mined cavities or tunnels approximately 250 to 1000 m below the surface (http://world-nuclear.org/info/inf04ap2.html). A fundamental premise for the disposal system is that it is intended to operate independently without relying on monitoring or institutional controls (although the system may be operated with such controls for a limited time after closing the repository) (18).

The long-term safety of a mined geologic repository is based on the containment and long-term isolation provided by a multibarrier system consisting of engineered and natural barriers (and their sub-barriers). The basic idea is that any one barrier may be insufficient to ensure the necessary degree of containment and isolation and that other barriers need to be able to compensate and provide additional insurance (18). The disposal system is built to maximize the redundancy of barriers to ensure that the performance of the disposal system is acceptable even if some components of the repository system fail to perform as expected.

Engineered barriers are designed to completely contain the waste initially, during the period of highest toxicity and greatest public concern. Since no engineered barrier can guarantee complete containment over the extraordinarily long time during which some components of the waste remain hazardous, limited releases of radionuclides from the engineered containment system are to be expected at some point far in the future. It is at this point that the natural barriers surrounding the geologic repository combine with the engineered barriers to attain the desired performance. The main functions of the natural barriers are to shield the repository from changes in the geologic environment, promote performance of the engineered barriers, delay radionuclide transport, and allow for dilution of radionuclide concentrations to limit exposure and ensure safety (18). As an example, Figure 3.1 illustrates the main barriers in the Swedish program for high-level radioactive waste disposal.

3.1 Engineered Barriers

The engineered barriers of a mined geologic repository are comprised of a number of components that may be identified in terms of their safety function. The main components are the waste form, the waste canister, and backfill material, as well as tunnel seals and plugs.

The main safety function of the waste form is to provide structural stability and resistance to waste dissolution, slowing the release of radionuclides into the aqueous phase (19). Spent fuel is in a solid form and is typically encased in zircaloy or stainless steel cladding (13, 19). Fuel cycles using reprocessing produce liquid wastes that need to be stabilized in a solid form for disposal, often using materials such as borosilicate glass, ceramic, and glass ceramic (20). Numerous other waste forms also exist, although they represent smaller quantities of waste.

The safety function of the waste package is to contain the waste, prevent its contact with groundwater, and delay radionuclide transport for as long a period as possible. Two safety strategies for the waste package have been proposed. In one strategy, the container material is not corrosion resistant (e.g., carbon steel) but has sufficient thickness to substantially delay releases before corrosion penetrates the package. (The corrosion products can also play a role in retarding radionuclide transport following failure of the package.) The second strategy is to use a corrosion-resistant material such as copper or nickel-based alloys. In some nations, such as Canada, both are implemented by using a carbon-steel inner container and a copper outer shell (19).

Another engineered-barrier component included in many waste disposal programs is a backfill (or buffer) material that fills the space in the repository openings between the waste package and the rock. The backfill provides mechanical support to the repository excavation and limits rockfall damage to the waste packages, blocks preferential flow and transport pathways along the excavation, and retards radionuclide movement within the repository tunnels. In most geologic environments, the backfill material is a bentonite or a bentonite-sand mixture. In rock salt, the backfill may be made of crushed salt. Tunnel and shaft seals and plugs provide similar safety functions in the repository excavations between waste emplacement locations; they are often made of the same materials.

3.2 Natural Barriers

The geologic environment in which the repository is located comprises the natural barrier. Key characteristics for a successful natural barrier are (13):

- Long-term (millions of years) geological stability, in terms of major earth movements and deformation, faulting, seismicity and heat flow;
- Low groundwater flow at repository depths, which can be shown to have been stable for periods of at least tens of thousands of years;
- Stable geochemical or hydrochemical conditions at depth, mainly described by a reducing environment and a composition controlled by equilibrium between water and rock forming minerals;

- Good engineering properties, which readily allow construction and operation of a repository.

The rock in which waste emplacement occurs is referred to as the “host” rock. A number of host rock types have been investigated for repository development in various nations. These generally fall within the broad categories of crystalline rock, clay-based rock, salt, and volcanic rock. Natural barriers ensure isolation of the waste and provide a stable predictable environment. Isolation is needed to prevent human contact but also to shield the repository from fluctuations in climate and related effects on groundwater flow/composition and erosion/deposition of sediments. Isolation also concerns the flow rate and velocity of groundwater movement through the geological environment. Since transport with flowing groundwater is the main mechanism for radionuclide migration to the biosphere, the magnitude of flow (a) impacts the rate of radionuclide release from the repository and (b) the rate of arrival of radionuclides at some point in the environment that leads to human contact.

Some host rock types limit water flow as a result of very low rock permeability, which is typically true for many clay-based rocks and salt. In other cases, such as some crystalline and volcanic rocks, permeability may be higher because of natural rock fractures, but the hydraulic driving forces may be limited, again resulting in low flow rates. The mineralogy of the rock and the aqueous geochemical conditions also play an important role through chemical interactions between the rock, water, and radionuclides. These interactions can result in radionuclide partitioning between the mobile aqueous phase and the immobile rock surface, and cause a substantial delay in the rate of radionuclide migration, even for systems with significant flow.

3.3 Retrievability

An important design aspect of mined geologic disposal is the question of retrievability of the waste during the first decades or centuries after emplacement. There are two main reasons for wanting the option of retrieving the waste: (a) to reverse storage if performance of the repository is found to be unacceptable, and (b) to allow for recycling of the waste if advanced technologies in the future make this possible. To some extent, retrievability is at odds with the reason for disposal, which is to isolate the waste. Retrievability for mined geologic disposal varies according to the host rock type. Hard rock such as granite tends to allow for easier retrievability than soft rock like salt (21). Retrievability is also affected by the engineering design of a mined geologic repository—for example, the type of tunnel support and the use of backfill.

4 Physico-Chemical Processes Affecting a Mined Geologic Repository and their Studies in Underground Research Laboratories

At its core, the development of a geologic repository for the disposal of radioactive waste is a scientific and engineering problem. Public acceptance and regulatory requirements rely on an adequate scientific understanding of the physico-chemical processes within and around a waste repository, and a detailed knowledge of the geological characteristics of the repository site. As mentioned earlier, the design of a waste repository is expected to be such that it allows emplacement of waste into the repository with minimum risk, and that it provides waste isolation for hundreds of thousands of (and even up to a million) years into the future. These are unique expectations, far beyond what are expected of human-constructed engineering structures to date. Locating a repository in deep geologic formations takes advantage of the *in situ* conditions having geologic time scale. For example, at depths of 500 m, the age of the groundwater could be hundreds of thousands of years, clear evidence that groundwater flow at the site is very slow. The approach adopted by waste management organizations internationally is a systematic and careful investigation of the physical and chemical processes that may occur within and around a repository—from its initial stage of construction, to the time of waste emplacement, all the way to the time period long after the repository closure. These processes are evaluated based on field studies, laboratory research, and mathematical modeling, in order to assess their impact on the isolation performance of the repository far into the future.

Efforts along these lines in the countries planning for radioactive waste repositories have been substantial over the last 30 years, and often involve major underground research laboratories (URLs). URLs are systems of underground rooms at the anticipated repository levels (200–500 m in depth) that have been mined through tunnels or shafts. These URLs allow direct observations of conditions and processes at these depths and provide opportunities to conduct full-scale tests to evaluate the physical and chemical responses to repository construction, heat release, and chemical migration of emplaced waste, as well as to long-term natural events, such as seismicity and glaciation on the land surface.

The safety of a repository depends on various factors: (a) in the early stages, those factors affecting the stability of the waste form and the durability of the waste packages; (b) at later stages (when barriers may have been breached), those factors affecting the transport of radionuclides by flowing groundwater, from the engineered barrier into the host rock and eventually to the biosphere. The latter factors, which are mostly of a hydrogeologic nature, are the main focus in this section. We first present relevant physico-chemical processes that may occur during the lifetime of a nuclear waste repository and explain how these can affect the hydrogeologic characteristics of the host rock. We then introduce some major currently active URLs to convey the level of scientific efforts being applied in a number of countries.

4.1 Four Stages in the Development of a Geologic Repository

The development of a geological repository for radioactive waste can be divided into four periods (22). The first period of repository development may be defined as the repository *construction stage*, which extends from tunnel excavation to a few days after tunnel lining and ground support installation (if necessary for tunnel stability). The second period, called the *open tunnel stage*, lasts until emplacement of waste and backfill materials. Then there is the third period, named here the *exploitation stage*, which marks the start of the strong perturbation due to the decay heat generated by the radioactive waste. This stage lasts until a few hundred or thousand years after repository closure, when the waste heat has greatly decreased and its effects become less significant. Finally, the fourth period is the *long-term postclosure stage*, which is the main period of concern for long-term performance and safety assessment. It is typically during this period that the integrity of the engineered barriers becomes questionable and the potential release of radionuclides from waste canisters must be considered. Key issues are then the migration of radionuclides through the backfill materials and subsequent transport in the host rock. The isolation capacity of the geologic repository for the long term and on the large scale depends on (a) the initial hydrogeological characteristics of the host rock, (b) the potential perturbation of these host-rock characteristics as a result of near-field processes and effects occurring during the previous three stages, and (c) other changes in host-rock characteristics due to natural phenomena and events, such as seismic activity or changes in climate.

The key processes during these four stages of geological repository development are discussed in the following subsections, in the context of the different rock types considered suitable for hosting a geologic repository. Crystalline rocks or hard rocks, such as granite, have been selected in Finland, Sweden and China; indurated (hardened) clays are being investigated in France and Switzerland; and plastic clays are being studied in Belgium. Furthermore, in Germany, Japan, and the United States, salt is being considered as one of several host rock alternatives.

In a hydro-mechanical sense, crystalline rock and plastic clay or salt form the end members of various material classes. While crystalline rock is nearly perfectly brittle material, plastic clay and salt can be described as ductile or visco-elastic-plastic material, the latter having the important property that any fractures formed can seal in time through rock creep and deformation. However, near the walls of ventilated underground openings, brittle behavior is also observed in plastic clays due to suction conditions. Indurated hard clays and sedimentary rock are transitional materials, which are brittle at low water content, but ductile at high water content. These differences in geomechanical behavior are important to repository safety, because they influence the extent to which new transport pathways for radionuclides may be created near repository tunnels as a result of structural damage from tunnel construction, ventilation, and waste emplacement.

Key Processes During the Construction Stage

The construction stage represents a major perturbation of the rock formation near emplacement tunnels, with possible creation of new openings (fractures) in the subsurface rock and significant changes in the hydro-mechanical conditions on the new rock walls. The stress field in the rock is redistributed around the tunnels, and the tunnel wall surface is moves inward until restrained by tunnel lining and support (in the case of soft rock), or until it stabilizes by its own strength (in the case of hard rock).

Basically there are two sources of rock damage that may occur near the new rock walls. First, there is the potential for damage caused by the excavation method itself, and second, there are mechanical changes caused by stress redistribution around the newly excavated opening. In addition, there are the effects of back pressure on rock deformation by emplacement of tunnel lining and support (23). For hard and brittle crystalline rock, the excavation activity could by itself induce significant damage, depending on the excavation method used. For example, if drill and blast methods are used, an excavation damaged zone (EDZ) could extend from 0.1 m to as much as 1.5 m into the rock, increasing its permeability to flow by two or three orders of magnitude in this region. In contrast, direct excavation damage is not so significant in other rock types, especially when a tunnel-boring machine is used.

The stress redistribution around a newly excavated tunnel induces a multiprocess coupled response in the rock (24, 25, 26). The resulting rock movements cause a volumetric deformation of the pore space that, when coupled with the low rock hydraulic conductivity, gives rise to strong pore-water-pressure variations that will then dissipate with time. These pore-pressure changes have a significant influence on the effective stress state in the rock and may contribute to rock failure processes. Creating the underground opening also influences the hydrological properties of the clay rock. The region adjacent to the tunnel rock may change from water-saturated to unsaturated conditions (and suction can develop), which can change the behavior of clay rocks from plastic to brittle (27).

Key Processes During the Open Tunnel Stage

This stage may be defined as the period between the completion of excavation and lining installation and the emplacement of waste and buffer. It may last from a few months to a few decades. During this period, the rock wall is in contact with the atmosphere in the (typically ventilated) tunnel. The atmosphere, with its generally lower humidity, imposes a new hydric condition at the tunnel wall or the lining, with its own permeability and air entry pressure, thus changing the local effective stress. Importantly, this condition is not a simple equilibrium between the relative humidity in the air and in the host rock, since the hydric transfer processes depend on several other factors such as air velocity and skin behavior.

In the case of crystalline rock, while tunnel ventilation and temperature changes probably do not have a strong effect on mechanical properties, air entering the rock results in an oxidizing, two-phase flow condition in the EDZ. This oxidizing condition may cause chemical and biological activities and a possible clogging effect, whereas the two-phase flow implies a reduction of the effective water-permeability values.

In clays (and possibly also in salt), where mechanical properties are sensitive to moisture content, the effects of dynamic changes in humidity and temperature due to tunnel ventilation are larger than in crystalline rock. These changes cause rock desaturation, which, in turn, gives rise to capillary forces and hence an increase in clay cohesion and strengthening. At the same time desaturation may increase tensile stress (as a result of shrinkage) and the potential for bond failure, and may change the degree of property anisotropy. Furthermore, increases in humidity in the tunnel air can cause clay swelling and rock softening in the rock next to the wall. The former may increase compressive stresses, leading to additional damage to the softened rock. Cyclic seasonal changes in humidity and temperature over a number of years have generated discontinuities in the vicinity of the underground research tunnel at Tournemire in France (28, 29, 30). On the other hand, as time goes by these discontinuities may close and seal due to clay deformation and moisture-induced swelling, which can lead to a reduction in permeability to that of the undisturbed formation. A number of studies have been conducted to investigate swelling behavior and permeability evolution in clays (31, 32, 33, 34).

Key Processes During the Exploitation Stage

At this stage, waste emplacement represents the start of a period of thermal perturbation, backfill will be in place, and the repository will be closed. Decay heat from radioactive waste diffuses away through the backfill and the near-field rock to the far field. Groundwater will flow from the far-field host rock towards the emplacement tunnels, leading to resaturation of the backfill and the EDZ. This is a slow process governed by low rock permeability, and will not be uniform over the repository domain. Resaturation is also affected by heat release from the emplaced waste, which will tend to dry the backfill and rock close to the waste canisters, and cause the vapor to flow outward and condense in the cooler region away from the heat source. These transient changes in water content, associated with the interplay between resaturation and temperature gradient, may have a significant dynamic impact on rock properties, especially in clays and rock salt, where the rock strength is a sensitive function of water content (22). Heating will also generate transient pore-pressure buildup resulting from differential thermal expansion, leading to changes in effective stress state. Studies addressing heating effects using laboratory measurements and field tests include those by Delage et al. (35), Zhang et al. (36), and Gens et al. (37).

Key Processes During the Post-Closure Stage

A few hundred to a few thousand years after the closure of a nuclear waste repository, the heat generation from the waste will be much reduced. In repositories that use bentonite-based components as backfill material, a return of pore-water pressure to the original hydrostatic level will result in swelling of the bentonite. Major processes during this stage include self-sealing of fractures in clay and salt rock and bentonite materials, long-term chemical and biological degradation of backfill and rock materials, and the degradation of the tunnel support system. There is also concern that chemical reactions (especially those involving canister and rock support materials) may produce gases, the pressures from which could build up in the canister deposition holes and create stress-induced damage. The effects of gas production and pressure buildup on radionuclide transport have recently received considerable attention (38, 39, 40, 41, 42).

It is during this stage, perhaps after tens to hundreds of thousands of years, that the integrity of the waste form and the canisters may be breached and radionuclides might dissolve into the groundwater present near the canisters. Radionuclides need to first migrate through the backfill, where chemical retardation and sorption onto clay materials can significantly retard the transport. The retardation mechanisms depend significantly on the characteristics of the backfill that has undergone some physico-chemical changes due to heating from the radioactive waste and subsequent cooling. Then, as the released radionuclides migrate into the near field of the repository, the properties of the EDZ play an important role, in particular raising the question of whether connected flow paths have been generated. Radionuclides that emerge from the EDZ represent the source term for migration into the far field rock. Flow and transport in the far field involve a number of processes, which, for example, include flow channeling, dispersion, matrix diffusion and sorption in a host rock in which fracture pathways are present. Some of these processes retard solute transport, while others cause preferential flow faster than the average flow rates. A thorough understanding of these processes is essential for estimating the far-field migration of radionuclides, which in turn determines possible radiation dose or health risks.

All these factors have to be investigated in the context of possible long-term changes in the natural environment of the repository system, such as from glaciation and climatic change. For example, in Canada and Scandinavia, one would anticipate glaciation, which has a cycle of about 20,000 years and produces an ice sheet of 1–4 km thick weighing on the land surface. Other events to be considered over long time periods may have low probability but high impact. These are generally disruptive events such as seismic or volcanic activity, which have been included, for example, in the long-term safety assessment for the Yucca Mountain site in Nevada, United States (43, 44). Regarding climatic change and seismic events, there is some thought that perhaps their impact at repository depth may be limited, but nevertheless these possibilities must be evaluated.

4.2 Underground Research Laboratories

In this subsection, we shall present currently active URLs, which are being utilized in many countries to study various processes of importance described in the last subsection. The need for URLs was identified in the early years of research into geologic disposal. A first example is the Stripa Project (45), which was an international collaborative program of research in an abandoned iron mine in Sweden carried out over the years 1977 to 1992. The results of the project significantly advanced the state of science of fracture hydrology and rock thermomechanics, and demonstrated the value of concerted underground research at, or close to, the anticipated repository level. The success of the Stripa Project led to later development of other URLs specifically constructed for waste repository research. Among these were some major URLs no longer active today, such as the Exploratory Studies Facility (ESF) at Yucca Mountain (46). The ESF was distinct from other URLs in that the volcanic tuff unit proposed as repository host rock resides in the vadose zone above the groundwater table. Since the main transport mechanism for radionuclides from a repository is through water flow, a partially water-saturated site has certain advantages (47), but also has its own set of processes, which were systematically evaluated in the URL (43).

A list of major URLs with ongoing R&D is given in Table 4.1. These URLs are located at depths from 240 to 500 m. Some have been initiated in the 1980s, but still maintain very active research programs. Most are *generic* URLs (i.e., located at a site with representative rock, but not designated to host a repository) while others, such as the Onkalo URL in Finland (48, 49) or the Bure URL in France (50, 51) are at a potential repository location. The latter *site-specific* type serves not only a research purpose, but is often expected to have a prototyping and performance confirmation function, meaning that full-scale mock-ups of an eventual repository tunnel are built underground for early testing of engineered and natural barrier components. The formations being studied range from crystalline rock like granite to very soft plastic clay rock like Boom Clay at Mol, Belgium. Among URLs of the same rock type, there can be significant differences, such as the age of the formation (ranging from 30 million to 1.5 billion years), the salinity of groundwater, the fracture density, and the occurrence of major fracture and fault zones. In general, the objectives of URLs may be summarized as follows:

- To compare the data on rock properties and *in situ* processes obtained from geophysical surveys and surface-based boreholes with those from direct measurements in the URL at depth. To verify that investigations from the ground surface and boreholes can provide sufficient data concerning key safety-related properties of the rock at repository level.
- To develop and verify the methods and technologies needed for site characterization at depth.
- To study deep rock responses to excavation and to heating from the waste, and to study radionuclide migration processes in the host rock. To develop and verify numerical models for description of groundwater flow, mechanical deformation, heat transfer, radionuclide migration, and evolution of chemical conditions during operation of a repository and after its closure.
- To test and demonstrate the technology for carrying out repository construction, waste emplacement, backfill, and repository closure procedures, to ensure that all the components function at a high level for maintaining repository short-term and long-term safety.

In addition, URLs provide a way for international collaboration with fruitful cross fertilization of ideas and methodologies (52). URLs are also critically needed by training personnel for conducting the various tasks in repository development, including repository design, construction, field tests, and modeling for safety assessment. Below, we shall give a brief description of two selected URLs to illustrate the scope and effort of URL research.

The first is the Grimsel URL, situated in crystalline rock in the Swiss Alps at a depth of about 400 m in the granite and granodiorite of the Aar Massif formed some 300 million years ago. The tunnel system at the site, over a kilometer in length (Figure 4.1), has been used for a large number of field experiments since the beginning of its operation in 1984. Some of the experiments are indicated in the figure. In the current phase, the research program at Grimsel covers about 10 field tests and involves 17 research organizations from 10 countries as well as the European Union (53).

Of particular interest among the field tests conducted at Grimsel is the FEBEX experiment, an *in situ* full-scale heater experiment evaluating the thermal-hydro-mechanical (THM) behavior of the geologic repository (54). In this test, two heaters, used to represent the heat-releasing radioactive waste, were placed horizontally into a tunnel and surrounded by a swelling clay buffer constructed of compacted bentonite blocks. The two heaters were turned on in 1997 with the temperature maintained at 100°C at the bentonite-heater interface. In 2002, one of the heaters was removed, while the other has continued its operation to date, making it the longest experiment of this type. All through the years of operation, hundreds of sensors have provided detailed physical and chemical data on the bentonite and rock. Furthermore, samples of bentonite, materials, and used instruments from the area of the first heater, which was removed in 2002, were studied and analyzed (55). The results form a very valuable data set regarding the transient behavior of buffer and rock materials under natural conditions for over a decade. The current plans are to continue the heating and monitoring of the second heater until 2014, and then it will also be excavated in 2015.

Another series of experiments at Grimsel, conducted as part of the colloid formation and migration project (CFM), seek to better understand transport mechanisms in a fracture shear zone that could potentially form a fast flow path in the host rock (56). Radionuclides or other surrogate species were released into the shear zone, and then their arrival was measured at some distance away from the release point to measure the "breakthrough" as a function of time. Such tests were performed for different types of radionuclides, for sorbing and nonsorbing tracers, for transport with and without colloids present. Current CFM experiments directly evaluate the performance of backfill material with respect to swelling, erosion, and colloid generation by emplacing a bentonite plug into a borehole completed in the fracture shear zone.

The second URL example is the HADES (High Activity Disposal Experimental Site) excavated at 223 m depth in Boom Clay, a tertiary clay formation in Mol, Belgium. Since its construction in 1980, many experimental investigations have been conducted at the site. Figure 4.2 (top) shows the construction history of the HADES facility (57). The main tunnel is about 200 m in length, with an internal diameter averaging about 4 m, from which experiments were conducted in boreholes and side galleries. An extensive summary is provided by Bernier et al. (26).

One current focus of work in HADES is the Praclay Gallery constructed in 2007, in which a Seal Test and a Heater Test were initiated in 2010 and 2011, respectively. The layout of the gallery is shown in Figure 4.2 (bottom). The Heater Test involves heating a 30 m long gallery section for 10 years with many monitoring sensors, for the purpose of investigating the THM behavior of plastic clay under the most hydromechanically challenging conditions occurring around a repository (58, 59). To this aim, the heated section of the gallery was fully saturated before starting the heating, and a hydraulic seal was installed to separate the heated from the unheated sections of the gallery. This installation makes up the Seal Test, which was conducted in 2010, and enabled testing of hydraulic seal functionality under heated repository conditions.

As can be seen from Table 4.1 and the above discussions, a considerable amount of scientific work has been conducted over the last 30 years or more to study various physico-chemical processes potentially occurring within and around a radioactive waste repository. Constructing a URL and performing various experiments in a URL are major investments. As a result, significant advances in geosciences and engineering have been made. These advances not only benefit repository construction and its safety assessment, but also represent major progress in the scientific fields of hydrogeology, hydrogeochemistry, geophysics, rock mechanics, and geology. The problem of geologic repository development, with the extraordinary requirement of being able to make convincing predictions many years into the future, is extremely challenging. There are no alternatives to conducting systematic and careful scientific and engineering research, which includes not only research in URLs, but also studies of natural analogues (60, 61). This is indeed happening in many of the countries with radioactive waste management programs today.

5 Recent Trends in Assessing the Long-Term Safety of Mined Geologic Disposal

This section describes the current practice and recent trends in assessing the future safety of a geologic disposal site, in order to provide a basis for regulatory (and societal) approval. As discussed in the previous section, any safety assessment needs to start with an adequate technical understanding of how the main waste-isolation barriers behave. Based on a solid technical foundation, a safety case can then be made, in which various lines of evidence are presented to quantify and substantiate that the repository will be safe over a long time period, and that the predicted performance meets regulatory standards.

5.1 Safety Standards for Repositories

While management of high-level radioactive waste is a national responsibility, several multinational organizations have played an important role in establishing a consensus on the principles of waste disposal and harmonizing safety standards and best practices for safety assessments among different countries. The most important international bodies are the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA). In part because of the consensus building of the IAEA and NEA, there is general agreement internationally on the fundamental principles and ethical duties of radioactive waste management, which require, for example, that future generations shall not shoulder an undue burden from today's waste and shall not be exposed to greater levels of radiation than are acceptable today (62, 63).

Differences remain between national waste-management policies regarding the specific safety standards that should be used to judge the suitability of a geologic repository, as well as the methods for demonstrating compliance with the standards (2, 63). Regulations typically define as primary safety standards a certain level of radiation protection for a “representative” person living in the vicinity of the repository under defined conditions (such as the consumption of a defined amount of groundwater from the area). Radiation protection is either defined as maximum radiation dose or is given in terms of health risk limit, or both. The main health risk associated with nuclear waste disposal is the potential of long-term low-level radiation exposure, which increases the risk of cancer or genetic mutation (65, 66). The health-risk limit is usually defined as the maximum likelihood of the representative person suffering health effects during his or her lifetime, measured in terms of probability per year. Dose and health risk are connected via “dose-to-risk” conversion factors. There is ongoing discussion on the uncertainty of “dose-to-risk” factors, caused by the difficulty of assessing health effects resulting from chronic radiation exposure (21, 67), and it has also been pointed out that health impacts might change in the not-too-distant future because of the expected progress in preventing and curing cancer (68).

Today, most international programs have converged on comparable dose constraints and risk limits as safety standards, to be demonstrated for time periods ranging from 10,000 years to a million years. Some countries have different safety and performance standards for the first several thousand years of repository lifetime compared to the remaining time period. Dose constraints for the earlier time periods vary between 0.1 and 0.3 millisievert per year, while risk limits vary between 10^{-5} and 10^{-6} per year. In comparison, the global annual average effective dose from typical natural background radiation is about ten times higher, at approximately 2.4 millisievert (66), and the risk of 10^{-6} per year is about twice the risk of being struck by lightning (21). This immediately invites the question (not discussed in this paper) as to how the public perceives different types of risk and how public acceptance might be improved by better risk education (69, 70, 71). In the context of providing multiple lines of evidence for the safety case (see next section), the value of additional safety indicators—complementary to the regulated safety standards—has received increasing attention (72). Examples of useful additional indicators are quantities describing the performance of sub-systems, such as the longevity of an engineered barrier or the magnitude of groundwater flow through the EDZ.

5.2 The Safety Case

Organizations responsible for implementing waste-management solutions generally present a safety case to the regulators or other decision makers at specific points in the process of repository development (72, 73). What is meant by safety case is a synthesis of evidence, analyses, and arguments to quantify and substantiate that a repository will be safe over a long time period. A central element of the safety case is a quantitative assessment of the future performance of the repository system, via comprehensive modeling studies, followed by a comparison of the results with the regulatory standards (see Section 5.3). The guiding principles behind a safety case have evolved over the last decade, as it was realized that building confidence in long-term safety assessments requires more than just the results of quantitative performance predictions. The safety case, as it is understood and accepted today, needs to also present independent lines of (sometimes qualitative) evidence and reasoning to support the quantitative assessment (and the assumptions made therein), and to provide decision makers with a basis for judging whether sufficient confidence exists in the performance evaluation (73). Independent lines of evidence may take the form of a combination of alternative predictive models, may involve broadbrush "insight" models based on first principles, or may utilize independent results from natural analogues (21). For example, principles of thermodynamics may guarantee the stability of copper (a canister material in some designs) in deep anaerobic groundwater. Or the existence of ancient natural uranium deposits may provide evidence that radionuclides can be stable in a geologic environment over millennia (72).

Typical safety cases will start with a description of the overall safety strategy for the repository, followed by an explanation of the assessment basis, a demonstration of evidence, analyses, and arguments, and finally a synthesis of results (see Figure 5.1). Guidance documents call for transparency in the presentation, traceability with respect to all key assumptions, flexibility in planning and implementation, and openness regarding remaining questions (72, 73). Chapman and McCombie (21) compiled key principles of safety cases that help reduce uncertainty and increase confidence, as follows:

- Use robust designs and analyses
- Aim for simplicity
- Apply good science
- Use a structured approach, including iterative assessments
- Use multiple lines of reasoning, a range of models, and natural analogues
- Document the elicitation of expert judgment (74)
- Perform quality assured analyses and have these peer reviewed

Most of these principles are straightforward, but the first two items deserve further discussion. Robustness refers to the repository system itself but also to the analyses used for assessing safety. A robust repository system starts with a stable geological environment in which key characteristics are unlikely to change significantly over long time frames. Robustness extends to the engineered barrier components that need to be well understood, tested, and resistant to degradation under a broader range of conditions than expected in the geological environment. Robustness is also related to the degree of redundancy achieved by having multiple barriers operating in concert to isolate the waste and prevent/delay radionuclide transport release to the biosphere. It is important that such complementary safety function, and the level of redundancy as a function of time, is demonstrated by conducting quantitative safety assessments for specific scenarios in which barriers are assessed individually (see following section). Robustness and simplicity are closely associated. Aiming for a repository site with simple geology, physics, chemistry, and design enhances transparency of and confidence in the safety case, and will furthermore allow for less complexity (and more robustness) in the safety analyses.

5.3 Quantitative Safety Assessment

What is meant with quantitative safety assessment is a "quantification of the overall level of performance, analysis of the associated uncertainties, and comparison with the relevant design and safety standards" (18). Quantitative safety assessments are an important contribution to the development of the long-term safety case for deep geologic disposal of radioactive wastes. In addition to contributing to the safety case for a repository, quantitative safety assessments also aid in identifying key processes relevant to safety and focusing research, provide an understanding of the value of individual barriers, and allow comparison between alternative waste-management options (18). Note that we use in this paper the term “safety assessment” for other labels sometimes used in the literature (e.g., “performance assessment”) (75, 76).

A quantitative safety assessment generally needs to provide answers to the following questions: (a) What are the performance-relevant features, events, and processes (FEPs) that need to be considered? (b) How likely are these? (c) What are their consequences? (d) How reliable (or how uncertain) are the answers to the first three questions? A typical workflow starts with a systematic selection and analysis of FEPs that can influence performance of the specific site, usually starting from the review of comprehensive generic FEPs databases (77). The next step is to develop the conceptual and mathematical models for predicting individual components of the repository system. After the component models (or submodels) have been tested to establish confidence and parameter ranges (including establishing their uncertainties), they need to be linked with each other in a system-level model of the entire repository. The system-level model can then be applied to determine the behavior of the whole system under consideration. Because different sources of uncertainty need to be accounted for—scenario uncertainty, conceptual model uncertainty, and parameter uncertainty—this final step generally involves some quantification of uncertainty, usually conducted by repeating simulations over a sufficient number of alternative scenarios, conceptual models, or parameters.

Review of the recent literature suggests consistency between international programs on basic principles and methodologies of safety assessments (73, 78), but also reveals a few areas where open questions remain and discussion is ongoing. Below, we briefly touch on two of these areas: (a) how the fidelity of the system-level model and their underlying submodels can be ensured, and (b) how uncertainty and sensitivity should be treated.

The overall fidelity of a safety assessment model starts with the fidelity of the individual submodels that support the overall system level model. These are typically detailed process-driven models, which need to be thoroughly tested and validated against experimental data. As mentioned in Section 4.2, URLs offer valuable data for model testing, because experimental studies of the expected conditions in emplacement tunnels and the surrounding rock can be conducted at or near full spatial scale. Time, however, is another issue. No experimental study can even marginally approach the long time periods that quantitative safety assessments need to cover. Confidence in geologic modeling over long time scales can be gained from natural analogues (60). An example of a natural analogue is the Peña Blanca uranium ore deposit in northern Mexico, which contributed to a better understanding of the long-term transport processes and of the long-term stability of minerals in arid regions similar to the Yucca Mountain site (61). Almost all national disposal programs are therefore involved in natural analogue studies and use data—often qualitative, sometimes quantitative—from analogues to support model predictions.

For use in system-level safety assessment models, the results from individual component models often need to be simplified, in a process sometimes referred to as model abstraction. It is important in the abstraction process that the simplifications and assumptions made are realistic and appropriate, and that the uncertainties of the primary models are represented by their simpler surrogates (43). To ensure appropriate abstraction, the simplified models need to be carefully compared to the primary models, and the remaining differences need to be evaluated in the context of the overall system-level impact. Another concern for the fidelity of a system-level model is that output from one submodel is used as input for another, which can lead to consistency problems (79). The trend in recent years has been to reduce the number of submodels and the number of abstractions in a system level model. For example, advances in computer power may now allow simulating the near-field and far-field processes in one detailed model rather than a sequence of submodels, or may allow use of certain primary models in a system-level uncertainty analysis without simplification or abstraction. The distinction between a system-level model and a detailed process model is becoming increasingly blurry and will continue to do so in the future (79).

With regards to addressing uncertainty in long-term performance predictions, national disposal programs all agree with international guidance that uncertainty is an “unavoidable aspect of planning and regulating deep disposal programs” (21), but they differ considerably in how uncertainty is to be assessed in a safety assessment (2). Probabilistic safety assessments are evaluations in which the uncertainty of scenarios or parameters is accounted for explicitly by assigning probability values/distributions and conducting performance predictions over the whole uncertainty space, thus assessing “global” uncertainty. Deterministic uncertainty assessments, on the other hand, explore a subset of selected uncertainties by performing “targeted” simulations for variations from an expected case, thereby assessing “local” uncertainty (80). Regulators in the United States have required a probabilistic safety assessment for the Yucca Mountain site (43). In contrast, the Finnish, French, and German programs evaluate deterministically how a proposed geologic repository would perform for a small set of defined scenarios. A combination of probabilistic (for probable scenarios) and deterministic (for less-probable scenarios) uncertainty evaluation is called for in Sweden.

Most experts would probably agree that probabilistic assessments are more useful in theory because the entire uncertainty space is queried, but would also acknowledge that these methods are not necessarily simple nor are they straightforward. For example, because probability values or probability distributions functions are not easy to define, there may be a tendency to make conservative choices for parameters that are not well constrained, e.g., by selecting an upper-bound value or by choosing a very wide uncertainty distribution. Such intended conservatism can, in rare circumstances, lead to a reduction of calculated overall risk, a counter-intuitive result often termed “risk dilution” (79). A more likely outcome of conservatism in parameter choices is that the performance prediction does not represent a realistic assessment of risk (81). Since the results of *individual* submodels are propagated with the system-level model, the calculated *overall* risk can be overly conservative even if reasonable conservatism is employed in each submodel. To evaluate the importance of explicit and implicit conservatism, probabilistic safety assessments should generally be supported by (and compared to) deterministic calculations (82).

Another important question is whether sensitivity cases considered in a safety assessment should be bundled together and rolled up into one total dose value (lumping) or whether they should be treated separately (splitting) (80). In principle, lumping of scenarios or events ensures that all possible future conditions with their respective likelihood are incorporated into one (time-dependent) uncertainty estimate (43), but it also means that high-probability and low-impact scenarios are attributed to the same level of risk as low-probability and high-impact scenarios. Individual cases with poor performance might then either dominate over, or might be diluted within, a multitude of more favorable cases. Splitting of scenarios or events, on the other hand, has its disadvantages, because it is difficult to quantify the relative importance of various discrete cases and its aggregated overall performance. Nevertheless, several nations (e.g., Sweden) and institutions advocate the splitting of scenarios, in particular when less likely scenarios with natural disruptive events are considered (84, 85).

In reviewing the above considerations, it appears that a robust quantitative safety assessment for geologic disposal should consist of a *set* of separate, purpose-driven, and complementary performance predictions with probabilistic *and* deterministic calculations, as well as with aggregated total assessments *and* separate scenario/subsystem analysis. The latter would include, but should not be limited to, analysis of scenario classes. Separate performance calculations should also be conducted for individual barriers (e.g., "What if the engineered barrier would fail?") or other relevant sensitivity cases. System-level models need to be supported by demonstrations that the underlying primary models are valid. Because of the technical complexity of disposal systems, quantitative safety assessments can be so complicated that their logic, methodology, and outcome may be hard to comprehend even for experts, let alone the public (82). Repository programs may have to produce extremely complex safety assessments, but they should also develop simplified yet realistic versions for the general technical and public audiences (85, 86).

5.4 Long-Term Predictability

A topic of ongoing discussion in safety assessments is how to handle the long time scale over which the radioactive waste may remain hazardous (87, 88). Many factors defining the evolution of a repository involve complex processes that are quite challenging to predict over years or decades. Even the most stable materials and geologic environments, over long enough time scales, are subject to perturbing events and long-term changes, which make quantitative predictions more and more uncertain. Eventually, uncertainties can become so overwhelming that a quantifiable performance analysis may not be meaningful (e.g., 89, 90, 91). With the exception of France, however, most national programs today require safety assessments for time periods between 100,000 and one million years. The question arises then what level of protection should reasonably be required for such distant times and how compliance should be demonstrated.

The rationale for selecting time periods that encompass hundreds of thousands of years is based on the ethical principle that safety needs to be assessed for as long as the waste presents a hazard. This argument often involves comparison of the radiological activity of the waste with that of natural systems (see Figure 2.1), suggesting that typical waste returns to activity values below natural levels somewhere between tens of thousands to hundreds of thousand years. Another rationale is that the compliance period should extend beyond the time of predicted peak dose. In most disposal concepts, the maximum dose impacting the biosphere is expected after several hundred thousand years or even later, due to the longevity of the engineered barriers and the retention capacity of the host rock.

Advocates for shorter compliance periods have cautioned that predictions of several thousand years into the future are neither meaningful nor reliable because of the increasing intrinsic uncertainties of longer-term projections. Some have argued that 10,000 years is about the duration of the human civilization as we know it, and that the protection of individuals beyond that time is “not a reasonable expenditure of today’s resources” (91). Nevertheless, it appears that the international community is converging towards acceptance of a one- million-year safety assessment period, but, in an attempt to balance ethical and technical considerations, is advocating for “time-graded containment objectives” (21, 87). In this concept, different safety standards are defined for different time periods, with hard protection criteria used in the short term giving way to softer criteria in the very long term (based on 21).

- Initial Time Period of 500 to 1000 Years
  Total containment is proposed for this initial time period, which is the period of highest toxicity and greatest public concern. This time period may overlap with a period of monitoring and retrievability.
- Second Time Period of Up To 100,000 Years
  During this time period, a dose constraint on the order of 0.1 to 0.3 millisievert per year would be prescribed, similar to current radiological protection principles.

- Third Time Period of Up To 1,000,000 Years

  During this last time period, the proposed objective is that the eventual redistribution of the residual activity in the repository is equivalent to the range of natural radiation hazards. Thus it would be recognized and accepted that beyond the natural "cross-over time" (i.e., the time when even the longest-lived waste eventually returns to values below the natural toxicity level) there is no logical or ethical reason for trying to set radiation protection standards that are more strict than the range of natural radioactivity exposure experienced today.

There is no full closure yet on some of the questions being raised above (e.g., Blandford et al., 2011). However, it is clear that a safety case with a compliance period of up to one million years will have to be made in most international programs. What is not settled today is whether disposal safety over very long time periods should be demonstrated by quantitative (and possibly probabilistic) assessment of dose or health risk, or rather via qualitative or semi-quantitative reasoning. Proponents of quantitative methods maintain that these have value in a safety assessment as long as the large uncertainties involved with the calculation results are acknowledged. The argument is that quantitative calculations of dose and risk over such long times should not be viewed as a realistic prediction of the future, but rather as an illustration of potential impacts to provide evidence that supports other lines of reasoning and qualitative analysis (87, 88). Others maintain that the results from such calculations are so questionable that they should not be used to support decision making (90, 91, 92). Instead they propose rigorous quantitative safety assessment for the human time scale (thousands or ten-thousands of years), but prefer qualitative analysis for the geologic time scale.

6 Conclusions

Because of its long-lived toxicity, high-level radioactive waste requires disposal systems that can provide long-term isolation over very long times. Evaluations (and re-evaluations) by various countries and international organizations have identified mined geologic disposal as the most practical and effective way to ensure safe permanent disposal. Carefully selected and well designed geologic disposal systems with multiple, passive, engineered and natural barriers are expected to provide an acceptable level of safety for current and future generations.

There has been a considerable level of scientific effort on mined geologic disposal over the last 30 years in geological formations ranging from granitic rock to salt and clay. These research activities, which include the development and use of several large-scale URLs, have resulted in a better understanding of the physical, mechanical, and chemical processes expected within and near geologic repositories. URLs also provide unique opportunities for international collaboration that stimulates the development of new ideas and methodologies.

The long time frame associated with high-level waste requires that safety assessments for geologic disposal need to be carried out very far into the future. This requirement is a major challenge and can only be addressed in an integrated approach composed of several key elements: (a) the systematic and careful research of relevant processes through laboratory research, numerical modeling and field tests in URLs; (b) the detailed study of natural analogues to evaluate the long term behavior of natural systems related to fluid flow and radionuclide transport; and (c) the synthesis of quantitative safety analyses with a convincing science base and multiple independent lines of evidence in a transparent, traceable, and robust safety case.

Uncertainties are inevitable, however, and they need to be explicitly accounted for. Different methods exist to conduct uncertainty evaluations and more research is needed to determine which uncertainty quantification approaches are best suited. Of equal importance is that results from safety assessments and uncertainty analyses need to be formulated in a clear way understandable to the public and stakeholders. Open communication is critical to achieve and maintain public support and acceptance over the long development period required for selecting, investigating, licensing, constructing, and operating a repository system.

Summary Points

1. Radioactive waste requires complete containment on the order of a few thousand years, because of the high-radiation intensity of the waste during this initial period. Substantial isolation over much longer time periods, up to a million years, is needed to limit exposure to the waste because of the potential hazard of chronic low-radiation-dose exposures.

2. Mined geologic disposal is considered the most practical and effective way to safely isolate the waste over long time periods. It relies on multiple, passive, engineered and natural barriers to provide an acceptable level of safety for current and future generations.

3. Many technical aspects of the waste disposal problem have been studied systematically for a variety of geologic environments, and this effort has resulted in significant advances in associated aspects of engineering and geosciences.

4. Regulatory and public acceptance requires the development of a safety case for a given disposal system. The safety case ideally contains multiple lines of evidence, including quantitative performance predictions supported by laboratory and field data, plus qualitative information from natural analogues or other geological observations.

Future Issues

1. Having to deal with the radioactive waste remains one of the main challenges to the prospect of global nuclear energy utilization.

2. While many experts believe that the disposal of waste in a geologic repository is technically feasible and safe, public perception is mostly negative. Several countries and organizations have come to realize that public acceptance of waste disposal sites can be increased by active stakeholder participation in the decision process. Also, countries like Finland, Sweden, and France are moving forward with their license application process and are expected to have operating geologic repositories in the 2020 to 2025 time frame. A successful repository operation in one of these countries would possibly increase confidence in other nuclear nations.

3. Despite decades of R&D and significant advances regarding the technical complexities of disposal, there is still need for continued research because of the unique requirements and inevitable uncertainties of long-term predictability into the far distant future.

4. Questions remain as to which safety standards are reasonable in light of technical and ethical considerations and whether adherence to these standards over very long time periods should be (or can be) demonstrated by quantitative analyses or rather qualitative reasoning.

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World Nuclear Association: http://world-nuclear.org/info/inf04ap2.html

Tables

Table 4.1: Major Currently Active URLs

URL	Rock Formation	Depth	Year Initiated
Grimsel, Switzerland	Crystalline Rock	~ 400 m	1984
HADES, Belgium	Boom Clay[c]	~ 240 m	1984
Äspö, Sweden	Crystalline Rock	~ 460 m	1995
Mont Terri, Switzerland	Opalinus Clay[c]	250–320 m	1996
Tournemire, France	Argillite[c]	250 m	1996[a]
Bure, France	Argillite[c]	500 m	2000 [b] (completed 2009)
Onkalo, Finland	Crystalline Rock	400–500 m	2004 [b]
Mizunami, Japan	Crystalline Rock	500 m	2005 [b]
Horonobe, Japan	Sedimentary Rock	300 m (500 m planned)	2006 [b]

[a]Year when two tunnels for repository research were drilled off a century-old railway tunnel.

[b]Year URL construction started; the construction is ongoing, but field testing has already been initiated in the completed part of tunnel.

[c]Opalinus Clay and Argillite are indurated clays, representing rock with strength in between crystalline rock and plastic clay such as Boom Clay.

Figures

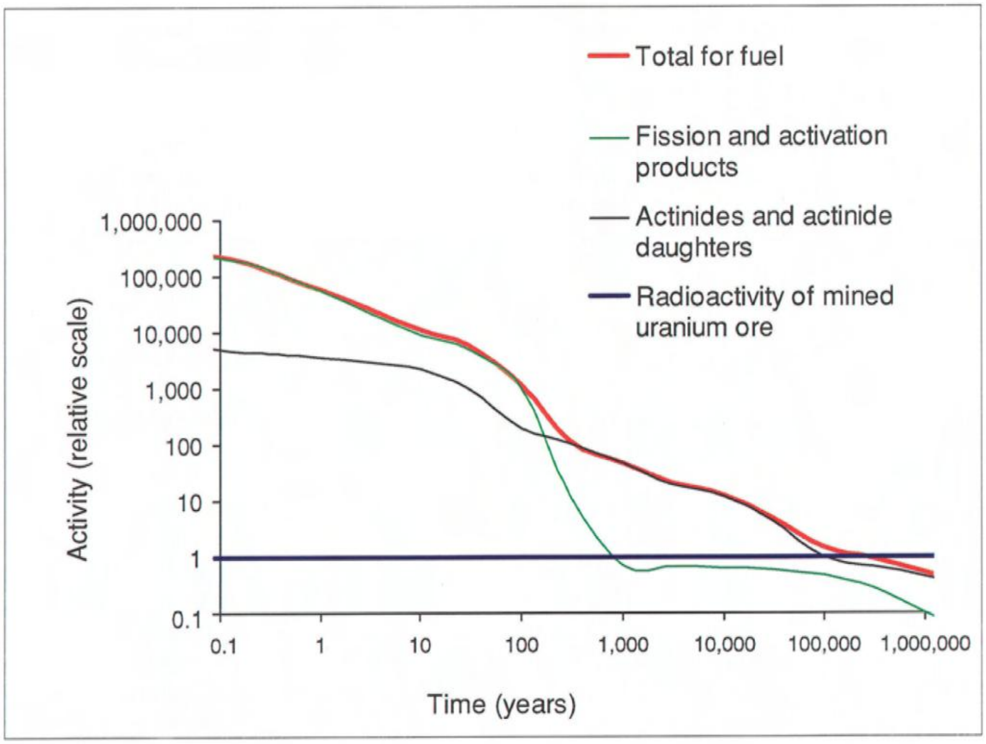

Figure 2.1: Radioactivity of spent fuel relative to the natural radioactivity of mined uranium ore [from Hedin (7)].

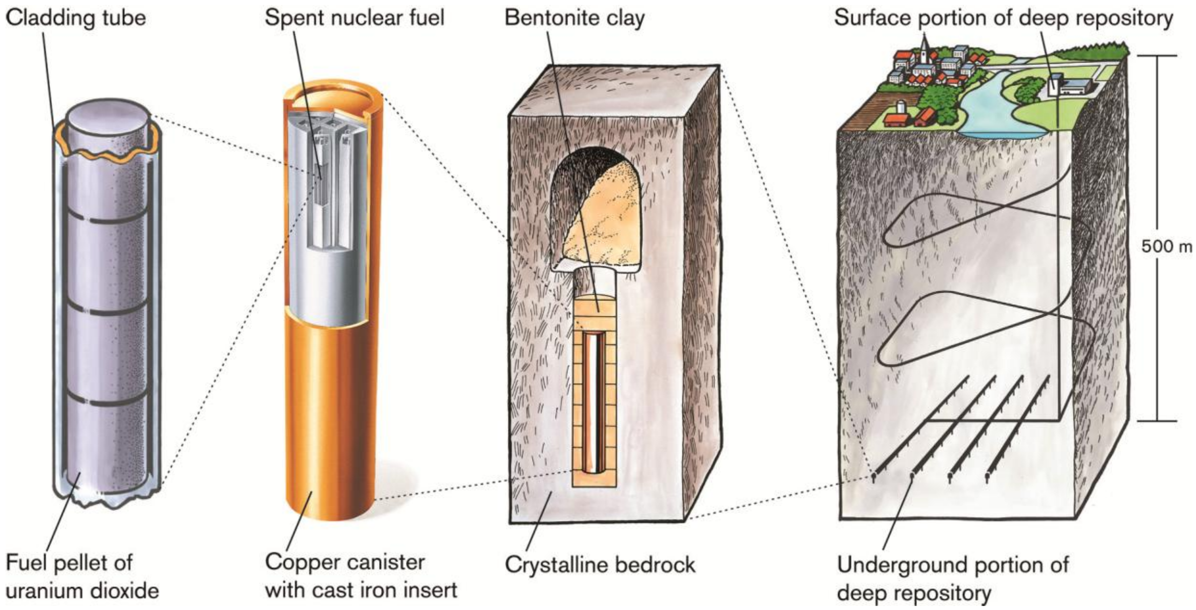

Figure 3.1: Barriers for radioactive waste disposal.
Source: SKB (http://www.skb.se/Templates/Standard____24109.aspx)

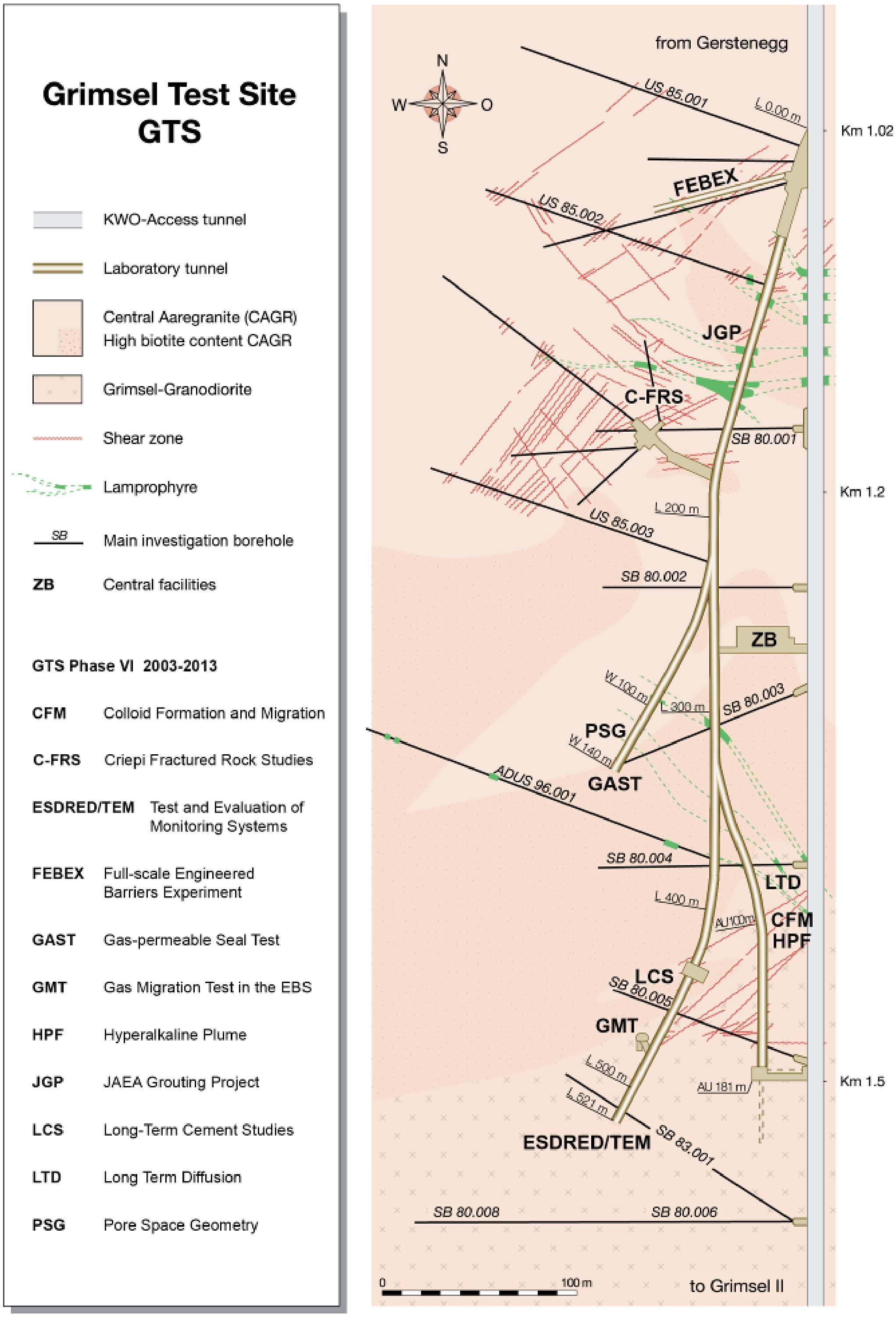

Figure 4.1: Layout of the Grimsel URL tunnel network [from Vomvoris et al. (53)]. The list of field tests in Phase V1 (2003–2013) are indicated in the lower left part of the figure.

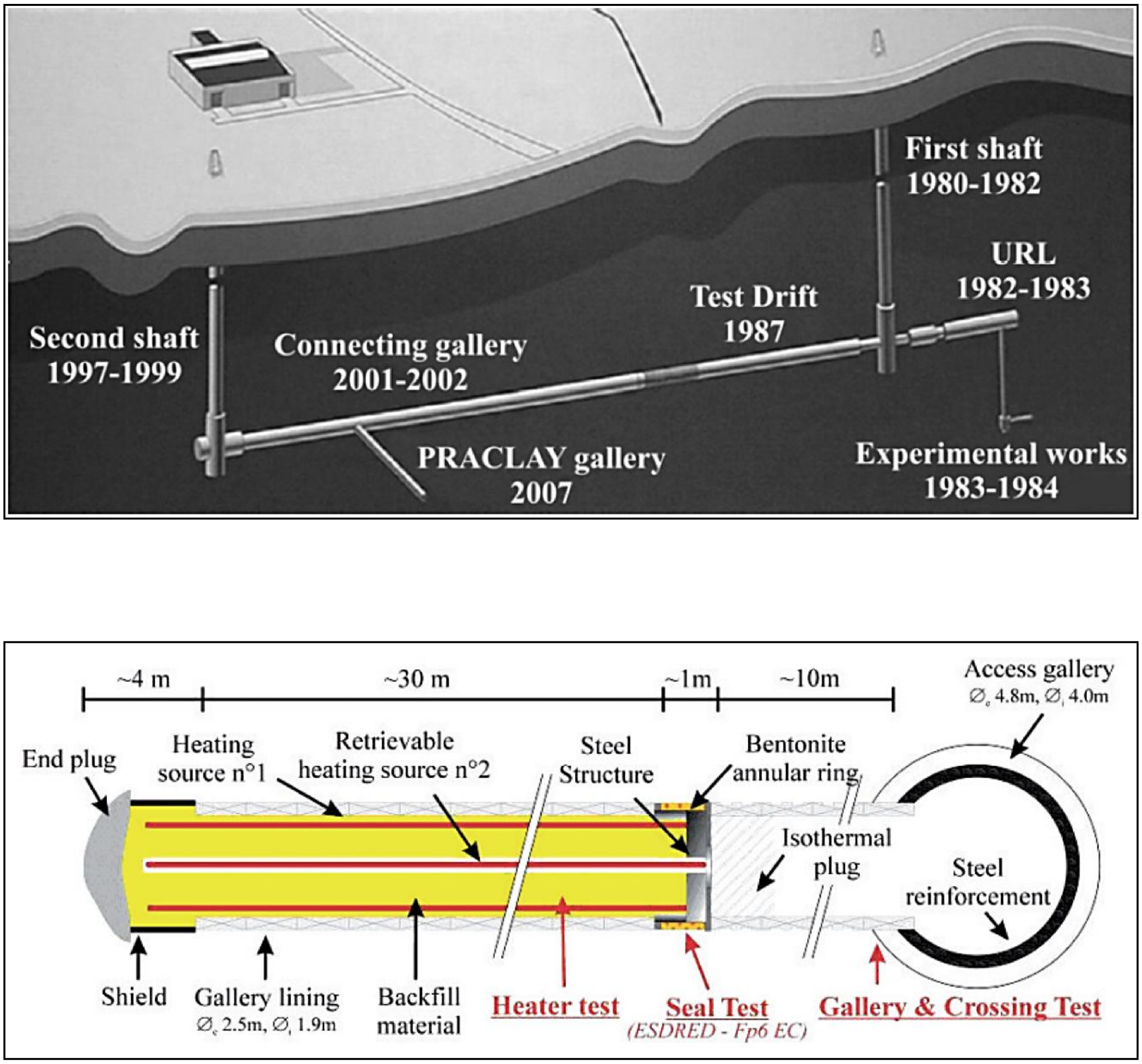

Figure 4.2: Layout of HADES URL at Mol, Belgium (top). Schematic of the Praclay In-Situ Experiment constituted of the Gallery and Crossing Test, the Seal Test, and the Heater Test (bottom). [Van Marcke and Bastiaens (57)]

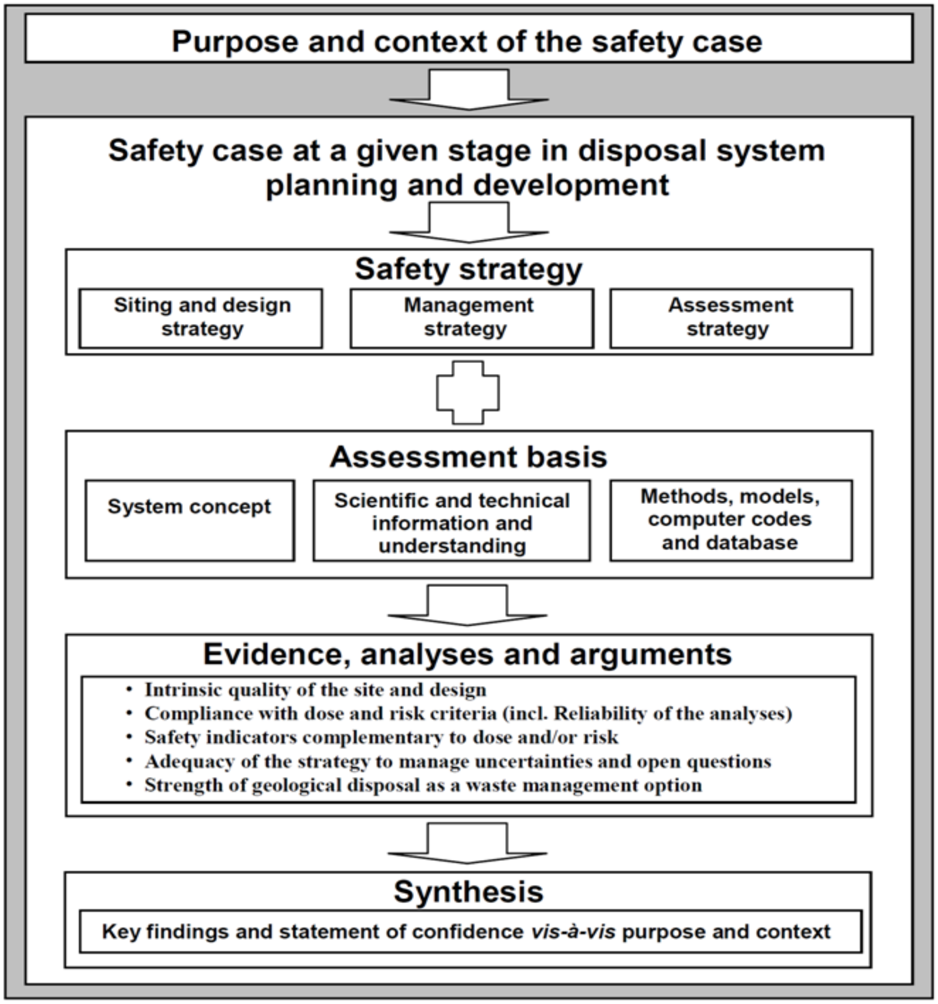

Figure 5.1: Typical elements of a safety case [NEA, (72)].