

Geological disposal of radioactive waste

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ABSTRACT

Some types of radioactive waste remain hazardous for thousands of years. Disposal of this long-lived waste in stable geological formation is the best thinkable solution according to the current state of technology and science. This is done by placing packages with radioactive waste in an underground facility, hundreds of metres below the land surface. After closure of a facility, isolation of the waste and containment of the radionuclides are achieved by a disposal system consisting of engineered barriers, the geological formation and surrounding rock formations. This geological disposal of radioactive waste has been studied in the Netherlands for more than four decades. Permian and Triassic rock salt formations are investigated since a facility can be constructed in this rock and its ultralow permeability ensures containment of radionuclides. Upward movement of salt (diapirism) and dissolution due to groundwater flow (subrosion), however, can disrupt the key aspects of rock salt. These natural processes are studied to assess the likelihood of radionuclides from the waste to enter the biosphere. The suitable disposal depth is determined by considering plausible natural processes, such as climate change (including ice ages) that in the future may interfere with underground disposal sites. Paleogene clay formations are an alternative rock type for the disposal of radioactive waste. New techniques have become available to construct underground facilities in these low-permeability argillaceous sediments. Emphasis is now put on obtaining freshly cored material at suitable disposal depths to gain further knowledge on the geotechnical properties of these clays.

<< Emplacing drums with solid processed waste in the Dutch storage facility for Low and Intermediate Level Waste. Forklift trucks are also envisaged for the stacking of waste packages in a future geological disposal facility. Photo: COVRA.

Introduction

Every material on earth contains so-called radionuclides, i.e. natural isotopes of elements that release radiation as they change into another element and become more stable. Only when the radionuclide content of a substance exceeds certain thresholds, is it called 'radioactive'. These thresholds, the exemption and clearance levels, are derived for both natural and man-made radionuclides. The materials below these levels can be used, recycled or disposed of without any radiological detriment to health and the environment. The exemption and clearance levels are radionuclide-specific and are regularly updated with latest insights with respect to health damage caused by ionising radiation (EC, 2013).

Radioactivity

Radioactivity has been present on earth since its origin some 4.6 billion years ago. Radioactive potassium, uranium and thorium in rocks and soils are examples of natural radionuclides that have a primordial origin (Cinelli et al., 2019). Some natural radionuclides are continuously generated by neutron capture such as nitrogen-14 (non-radioactive isotope), which in the atmosphere reacts with

a neutron to form carbon-14 (radioactive isotope). The neutrons are created from the interaction of cosmic particles, such as high energetic protons from the sun and other stars, with particles in the atmosphere (Kovaltsov et al., 2012). Natural radionuclides can also be generated deep in the earth's crust from neutrons in uranium ores. A very recent source of radionuclides is anthropogenic, for example resulting from neutron irradiation in a nuclear reactor.

Radioactive waste

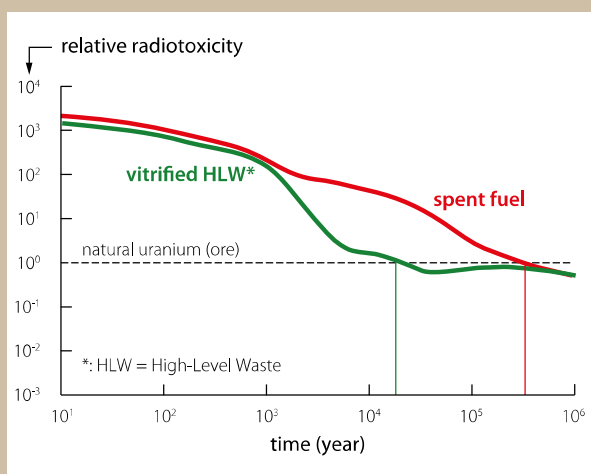
Radioactive material becomes radioactive waste when no future use is foreseen. Radioactive waste can arise during the generation of nuclear power, production of medicine, research and education, use of diagnostics for human health care and the examination of the integrity of engineered constructions. Radioactive waste can also be collected from facilities in which natural radioactive materials are concentrated, for instance in pipes and casings at oil-field production sites (USGS, 1999).

Radioactive waste needs to be disposed of for a long duration in a safe location disconnected from the biosphere. The design of a final, long-term location for disposal of waste has to take into account the period that waste remains hazardous and needs to consider social accepta-

Radiotoxicity

The potential impact of radionuclides on humans is best characterized by their 'radiotoxicity' rather than their radioactivity. Radiotoxicity is a measure of the radiation doses that would result if all the radionuclides in a given amount of waste were to be dissolved in water, and subsequently drunk by humans (Hamstra & Van der Feer, 1981). Although entirely hypothetical, this allows for the comparison of the hazardous nature of different types of radioactive materials. The figure shows a comparison between the radiotoxicity of spent fuel from a plant like the Borssele Nuclear Power Plant and the radiotoxicity of natural uranium ore.

The declining radiotoxicity of spent fuel and vitrified HLW is shown as a function of time after the fuel has been taken out of the reactor or, for vitrified HLW, after it was manufactured, following the reprocessing of the equivalent quantity of spent fuel. The curves are shown normalized to the radiotoxicity of the amount of uranium ore that was originally used to make the fuel. When fuel comes out of a nuclear reactor, it is many thousands of times more radiotoxic than the uranium ore from which it was manufactured, but this diminishes significantly over a period of a some hundreds of years. The 'crossover' time, when spent fuel has a similar level of radiotoxicity to the original ore, is in the order of hundred thousand years. Vitrified HLW has an equivalent 'crossover' time of only about 20,000 years (Gruppelaar et al., 1998). The long time scales are the reason for safety assessments to consider potential impacts on future generations for several millions of years ahead.



bility. The necessary period for isolation can be determined by the required decay time for the waste to achieve the same radiotoxicity (see Textbox 1) as a natural material (Hamstra & Van der Feer, 1981). It takes about 200,000 years for spent nuclear power fuel to achieve the same radiotoxicity as natural uranium ore, and 20,000 years for the vitrified waste-forms arising from recycling of spent fuel (Gruppelaar et al., 1998). These periods are too long to be managed by society and therefore a solution could be based on isolation by geological barriers. Spent fuel and vitrified waste-forms are called High-Level Waste (HLW). HLW needs to be cooled during storage and requires shielding for safe transportation and storage. Intermediate Level Waste requires shielding only. Low and Intermediate Level Waste (LILW) has the lowest radiation levels. It is possible to stand next to a package LLW without additional precautions.

Disposal of radioactive waste

Radioactive waste can be disposed of in various ways, and the social acceptability of the way in which this is done has changed over time. For example, from 1967 until 1982, it was accepted that the Netherlands deposited packages with solidified LLW at specific locations in the Northeast Atlantic Ocean under strict conditions (NEA, 1985). In 1983, the Dutch government decided to stop off-shore disposal of waste packages (Alders et al., 1983; Winsemius, 1983). Since then, radioactive waste is managed in the Netherlands by COVRA, an abbreviation in Dutch for Central Organization For Radioactive Waste. The Dutch radioactive waste policy is based on above-ground storage for at least 100 years, followed by geological disposal of some types of radioactive waste. COVRA has a growing financial provision which guarantees sufficient financial resources to execute the future disposal of waste (see next section). The period of above-ground storage provides time to allow for a part of the waste to decay below the exemption and clearance levels. It also provides time to learn from experiences in other countries, to carry out research and to develop shared disposal facilities that could make disposal of waste more cost-effective (I&E, 2016). Countries with waste inventories larger than the Netherlands decided to build disposal facilities at the surface or near the surface for short-lived LILW. These facilities contain the waste previously destined for ocean dumping. Examples of these facilities are:

- Aube waste disposal facility in France operating since 1992 (international.andra.fr);
- Manche disposal facility in France that operated for 25 years (international.andra.fr);
- Forsmark disposal facility in Sweden operating since 1988 (Vahlund & Andersson, 2015).

Geological disposal

The geological disposal of radioactive waste, especially HLW, is considered the safest and most sustainable long-term solution. Geological disposal involves emplacement of packages with solid waste in a facility constructed in a stable geological environment, which is closed after filling. A geological disposal facility (GDF) is to be constructed at a depth of several hundreds of metres. The depth protects the waste from disturbance by human activities and disruptive natural processes such as erosion and flooding. Although even the most stable deep geological environments will eventually change with the passage of geological time (Ten Veen et al., 2015), the hazard potential of the waste will also decrease by radioactive decay as time passes.

The conceptual basis for geological disposal of radioactive waste is based on a multi-barrier system in which engineered and natural barriers act in concert to isolate the waste and contain the radionuclides (Chapman & Hooper, 2012). Two basic types of facility are considered; a subsurface system of tunnels (galleries) or vertical boreholes penetrating kilometres deep into the subsurface (see Textbox 2). A system of galleries is currently the focus of most studies in the Netherlands.

Around the world there are various examples of more or less successful geological disposal facilities. Between 1967 and 1978 Germany dumped 125,787 packages (124,486 LLW and 1301 ILW) in the former salt mine Asse II, south of Braunschweig (Gerstmann et al., 2002). The former mine proved not to be watertight after so much salt was mined and in 2013 a first-of-its-kind evacuation of all radioactive waste was decided. According to the responsible German Bundesgesellschaft für Endlagerung (BGE) evacuation will start in 2033. This example shows that the use of mines created for the extraction of resources may not provide a suitable base case for the construction of a GDF. In resource mining, often as much material as technically feasible is extracted. This is in contrast with the principle of geological disposal of waste in which the amount of host rock to be removed is minimized. A good example is the operational Waste Isolation Pilot Plant in the USA in which the rock provides the containment of the emplaced waste. This GDF is operational since 1999.

Finland is building a geological disposal facility for spent fuel in Olkiluoto (Fig. 21.1) and Sweden has given permission to construct a geological disposal facility for spent fuel in Forsmark. In both disposal systems, the crystalline Precambrian host rock provides isolation for the facilities built at 400 to 500 metres depth in which the engineered barriers contain the waste.

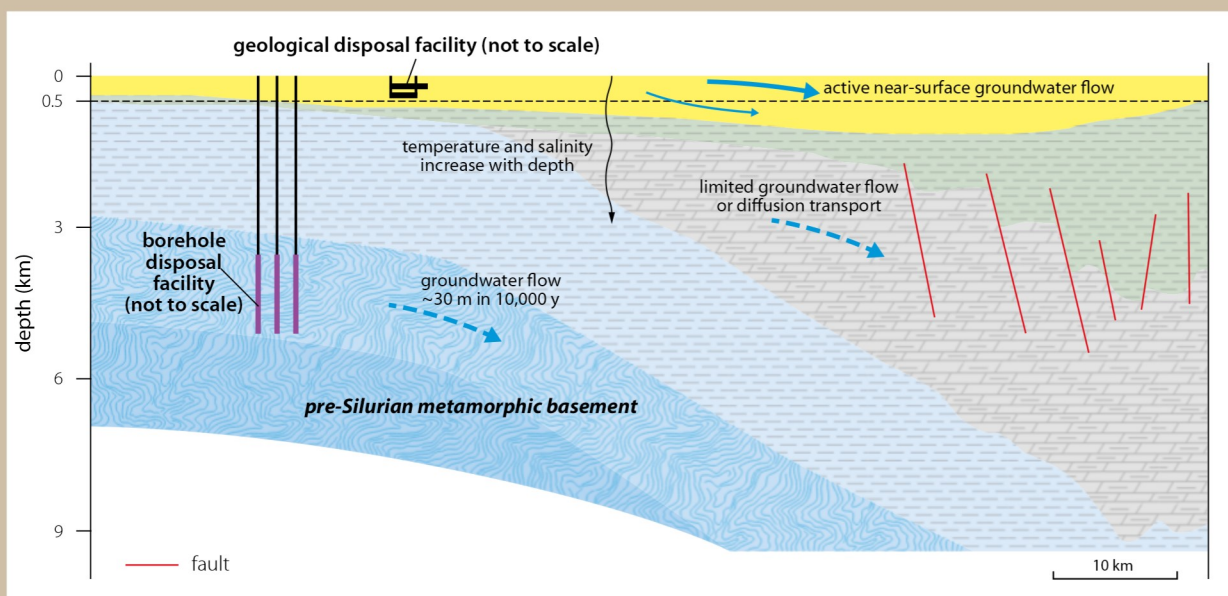
Disposal of waste in deep boreholes

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Disposal of waste in deep boreholes drilled from the surface has been the subject of research for several decades. The OPLA programme revised the emplacement method from a borehole filled with air into a borehole filled with brine to reduce the impact of the fall. The borehole would close itself by creep of the salt in which it would be drilled (Anonymous, 1986; OPLA, 1989).

An overview of the current state of science and technology of deep borehole disposal is given by Mallants et al. (2020). Technical advances in drilling for petroleum industry and geothermal energy over the past 20 to 30 years allow for greater depths, required safe distance between multiple boreholes and larger diameters to be realized. Subsurface conditions at a depth of more than a few kilometres favour stagnant or almost stationary pore fluids. This contributes to the isolation potential for disposal and creates a large safety barrier. The great depth of boreholes strongly determines the safety of this type of disposal, even more than the properties of the host rock. The isolation capacity is thus less dependent on a specific rock type, such as rock salt or clay. As a result, many new locations for disposal come into view.

A waste inventory for HLW in the Netherlands estimates that about three boreholes are required (Van de Vate, 2018). However, the dimensions of the packages of the vitrified HLW currently push the limit of feasible boreholes (Chapman, 2019). It is uncertain if these deep boreholes may offer a relatively cheap disposal concept since the estimation of the costs cannot rely on demonstrated techniques yet. Borehole disposal of LILW is not considered due to its large volume and associated envisaged costs. Further research is needed into the effect of the high temperature at depths of 3000-5000 metres which may increase the rate at which engineered barriers alter. Currently the Netherlands does not conduct research into deep boreholes but follows and examines developments through ERDO, the association for multinational radioactive waste solutions.



A conceptual model for deep borehole disposal (modified after Chapman & Gibb, 2003).

Research programmes into geological disposal of waste

Extensive research is required before a geological disposal facility can be constructed. The Dutch research for geological disposal of radioactive waste started in the 1970s aiming at waste that would arise from the production of 3500 MWe of nuclear power. This initiative was coordinated by

the government that formed the ICK committee, which is a Dutch acronym for Interdepartmental Commission for Nuclear Energy (*Interdepartementale Commissie voor de Kernenergie*). Research in the Netherlands has taken stock of international knowledge. Disposal of radioactive waste in salt deposits was considered the most promising solution in the USA (NRC, 1957) and especially salt domes were considered for the disposal of HLW in the Nether-

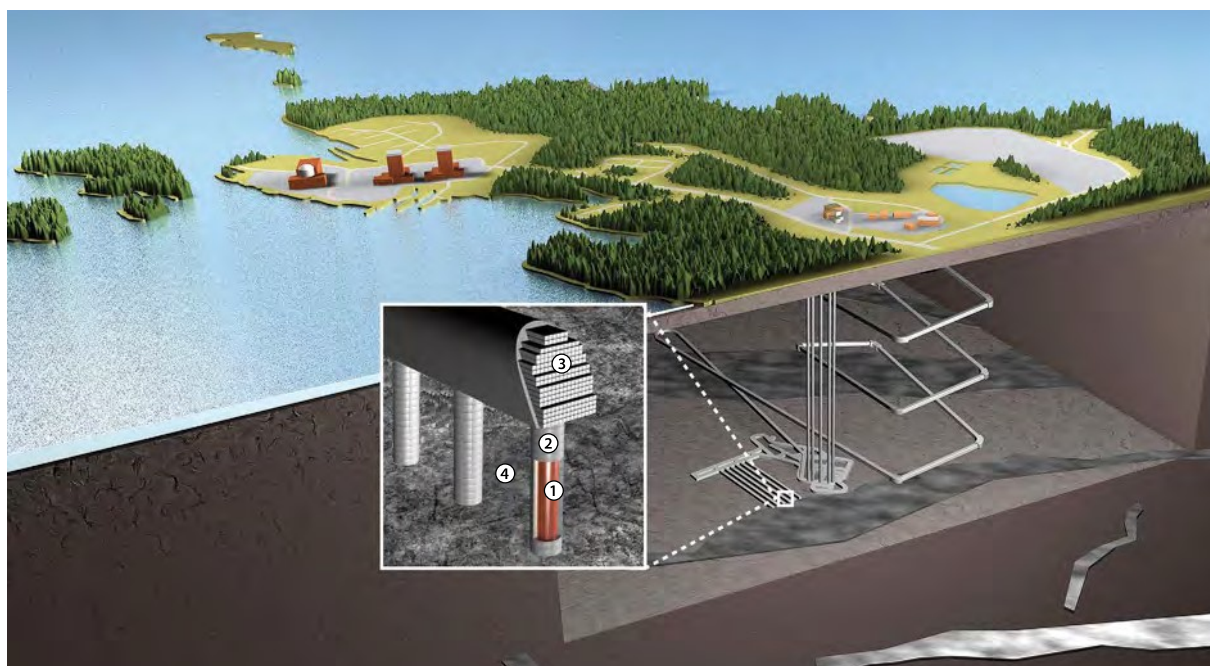


Figure 21.1. Schematic illustration of a repository at the Onkalo site near Olkiluoto Nuclear Power Plant, Finland. Engineered barriers have a highly insoluble ceramic matrix (not shown in the figure). Other components consist of: (1) a reinforced corrosion resistant copper container (diameter 1.05 m), (2) low permeable bentonite in a deposition hole (length 6.6–8.3 m) and (3) an access tunnel (height 6.95 m). In this example the natural barrier is formed by the granitic bedrock (4) at the depth (400–450 m) of the underground facility (POSIVA, 2012; Finnish Energy, 2021). Source: POSIVA.

lands (ICK, 1975; Van Aardenne, 1979). The following sections give an overview of previous research programmes on disposal of radioactive waste in the Netherlands.

Since the publication of the radioactive waste policy for the Netherlands (VROM, 1984), three research programmes focussed on potential host rocks in the subsurface of the Netherlands (Fig. 21.2). Initially these programmes focussed on Zechstein rock salt, but with time attention shifted to poorly indurated clays.

OPLA

The first research programme for geological disposal of radioactive waste was OPLA (Fig. 21.2), a Dutch acronym for onshore disposal (*OPberging te LAnd*). Next to OPLA, the disposal of waste in offshore salt domes, seabed disposal and the possibilities for interim storage of waste were studied in different programmes. OPLA was coordinated by the Geological Survey of the Netherlands (RGD) and financed by the Dutch government (Floor, 2012).

When OPLA started, solidified LLW was dumped in sea (NEA, 1985) and spent research reactor fuel was sent to the USA as part of the larger US nuclear non-proliferation treaty (IAEA, 2017). At that time, exploitation of gas from the Groningen field was in a starting phase and nuclear power was considered an appropriate alternative energy source. The shortage of oil from the Middle East in the 1970s, the so-called oil crisis, stimulated investigations

into increasing nuclear power generation in the Netherlands and thereby decreasing the long-term dependency on speculative foreign energy resources. At that time, the nuclear power plants of Borssele (490 MWe) in the southwest and Dodewaard (60 MWe) in the middle of the Netherlands were operational (I&W, 2020). The assumption was that the Netherlands would only need to dispose of limited volumes of vitrified HLW. The envisaged waste inventory was based on the volume of HLW arisen from these two plants and an additional 3000 MWe of nuclear power (OPLA, 1989, 1993). Following protests against nuclear power a discussion about the proposed increase in nuclear power was organized in parallel with OPLA (Van Aardenne et al., 1985).

In 1986 the Soviet nuclear power plant in Chernobyl (Ukraine) exploded and a plume of radionuclides from the reactor reached Europe and the Netherlands. Consequently, the governmental enthusiasm for nuclear power disappeared, despite the fact that the design of this Soviet plant did not comply with European standards.

The OPLA programme focussed on Zechstein salt since the construction method for tunnels in clay was not yet industrialized (OPLA, 1984). In the provinces of Friesland, Groningen, Drenthe and Overijssel (Twente) OPLA investigated 19 salt domes (diapirs) with a cap rock at the top of the dome and a depth of at least 170 metres, 15 salt pillows and 4 horizontally bedded salt formations at a

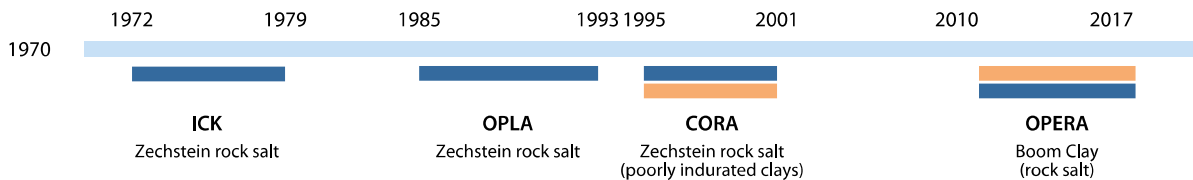


Figure 21.2. Research activities on host rocks and the three Dutch research programmes (Verhoef et al., 2020). Blue: rock salt, orange: poorly indurated clay. ICK: Interdepartementale Commissie Kernenergie (Interdepartmental Commission for Nuclear Energy); OPLA: OPberging te LAnd (onshore disposal); CORA: Commissie Opberging Radioactief Afval (Commission for Disposal of Radioactive Waste); OPERA: OnderzoeksProgramma Eindberging Radioactief Afval (Research Programme into Geological Disposal of Radioactive Waste).

maximum depth of 2200 metres. Geohydrological profiles of the sedimentary rock successions at each of these 38 sites were made to model the potential transport of radionuclides from the rock salt into the biosphere (OPLA, 1989). Of each site, the geological history during the Mesozoic and Cenozoic periods was investigated to make quantitative predictions on, for instance, the uplift rate of salt domes (Geluk & Wildenborg, 1988). In the extension of the OPLA programme, 45 sites with rock salt were found to be suitable for disposal of radioactive waste (OPLA, 1993). In the parliamentary evaluation of OPLA, the concept of retrievability was introduced in the Dutch radioactive waste policy to have control over the emplacement of waste packages and closure (Alders, 1993).

CORA

The OPLA research programme (Fig. 21.2) was followed by the CORA programme, a Dutch acronym for Commission for Disposal of Radioactive Waste (*Commissie Opberging Radioactief Afval*). This programme was also coordinated by the Geological Survey of the Netherlands (RGD) and financed by the Dutch government (Floor, 2012). At the start of CORA, solidified LILW was being stored in above-ground facilities as an interim solution. In the meantime, the USA had introduced a fee for accepting spent research reactor fuel (Messick et al., 2006). CORA primarily focused on the technical feasibility of *retrievable* disposal of vitrified HLW. Consequently, the investigations mainly addressed subsurface disposal of radioactive waste in subsurface facilities or in vertical boreholes drilled downward from the facility's gallery floor.

During that time, the Belgian disposal research programme demonstrated the feasibility of the construction of a tunnel in Rupelian clay in Mol (see section Construction of the geological disposal facility in indurated clay). The CORA programme therefore also considered Paleogene and Neogene clay formations (Simmelink et al., 1996). For both the disposal concepts in rock salt and clay an underground facility with short disposal galleries to emplace a single waste package containing vitrified HLW

was considered (Barnichon et al., 2000). The facilities were envisaged to be at a depth of 800 metres for rock salt and 500 metres for clay, i.e. below the level of expected future subglacial erosion. The difference in depth reflects the requirement for a sufficiently thick host rock on top of the facility of at least 200 metres for rock salt and 50 metres for clay. The minimum clay thickness was considered to be 100 metres. Rock salt can extend vertically hundreds of metres in a salt dome. In the developed concept, the disposal gallery was to be filled with an easily removable material such as crushed rock (rock salt or claystone) that would also provide shielding against the ionising radiation from the radionuclides in the waste. Retrieval of the waste package was envisaged by removal of the backfill and taking the waste package out (CORA, 2001). The Dutch government became convinced after the evaluation of CORA that the retrievability was technically feasible with these disposal concepts. The government also concluded that COVRA, as an organization that manages all types of radioactive waste, should be involved in research coordination (Geel, 2002).

OPERA

The last research programme was OPERA (Fig. 21.2), a Dutch acronym for Research Programme into Geological Disposal of Radioactive Waste (*OnderzoeksProgramma Eindberging Radioactief Afval*). This third programme was coordinated by COVRA and financed by the government and EPZ, the owner of the nuclear power plant in Borssele. This programme focused on disposal of radioactive waste in a facility hosted in the Boom Member of the Rupel Formation (Vis et al., 2016). This clay had been extensively studied in Belgium but knowledge for disposal of radioactive waste in the Netherlands in such a type of poorly indurated clay was much less developed than for disposal in rock salt.

By the start of OPERA, the local social acceptability for nuclear power had increased. In 2011, cores were allowed to be taken from boreholes in Borssele to investigate the subsurface for a new nuclear power plant. This drilling

activity also provided fresh Rupelian clay cores for research into disposal of waste. These cores were therefore also studied in OPERA (e.g. Behrends et al., 2015). However, the project for a new plant was not continued due to financial issues. The amount of waste from nuclear power generation (HLW) to be handled for disposal had increased, since the operational life period of the existing 490 MWe nuclear power plant in Borssele was extended from 30 years to 60 years. This doubling of the operational period did not result in a double volume of vitrified HLW since the radionuclide content per vitrified waste form unit was increased. The envisaged volume for disposal of this type of HLW was 70 m³ in CORA (CORA, 2001) and 93 m³ in OPERA (Verhoef et al., 2017). Also, at the start of OPERA, the operational lifetime of the research reactors was increased. The envisaged volume of spent fuel for disposal was increased from 40 m³ in CORA (CORA, 2001) to 104 m³ in OPERA (Verhoef et al., 2017). In addition, waste packages with solidified ILW and LLW were envisaged to be emplaced together with HLW in one disposal facility.

Although the disposal concept with a facility at 500 metres and clay as a host rock remained, there were three important differences between the concepts defined in CORA and OPERA. These concern three new features adopted from the Belgian disposal concept for HLW:

1. Only waste packaged in such a way that a worker can handle it without additional shielding will be emplaced
2. More than one waste package will be emplaced in each disposal gallery
3. Engineered concrete supports will also be envisaged for

the disposal galleries i.e. not only for the transport tunnels as studied in CORA

The final report of the third Dutch programme OPERA was submitted to the Dutch parliament in 2018 (Verhoef et al., 2017). The European directive to manage radioactive waste (EC, 2011) needed to be implemented in the Dutch policy during the execution of OPERA. This directive required a national programme for the management of radioactive waste and spent fuel (I&E, 2016). From then on, discussions about disposal of radioactive waste have been structured through this national programme (Van Veldhoven-Van der Meer, 2018).

COVRA's long-term research programme

The research programmes in the Netherlands have not been consecutive (Fig. 21.2) since it took time to secure the financial resources for each programme. The financial means for the future construction, operation and closure of a disposal facility have been and will be collected via a fee on the radioactive waste. Since 2018, the research for disposal of radioactive waste is financed directly by the waste fees, so as to secure continuity and prevent dormant phases in research. The research programme integrates all available knowledge in safety cases. Safety cases for disposal facilities in rock salt and poorly indurated clay will be updated each time the government needs to report to the European Commission about the progress made in the national programme, i.e. before 2025, 2035 and further (Verhoef et al., 2020). These safety cases are not site-spe-

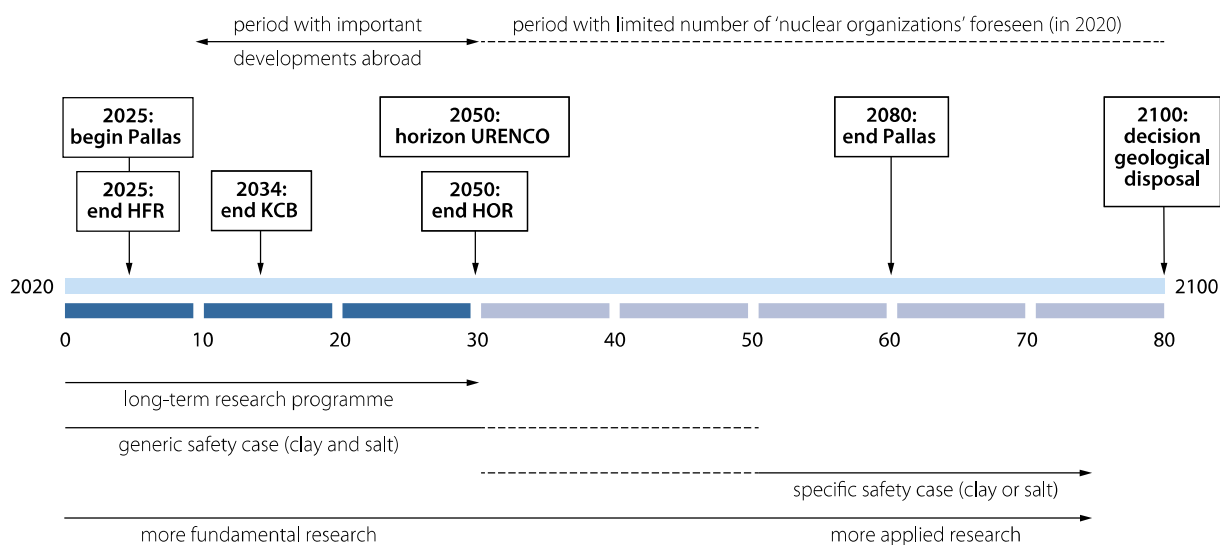


Figure 21.3. Timeline for the future of geological disposal of radioactive waste in the Netherlands (Verhoef et al., 2020). Pallas is a new nuclear plant for medical isotopes; High Flux Reactor (HFR) is the current nuclear plant for medical isotopes, KernCentrale Borssele (KCB) is a nuclear power plant, Hoger Onderwijs Reactor (HOR) is the nuclear plant for education and research, the URanium ENrichment Company (URENCO) was planned to be operating in the Netherlands until 2050 in 2020.

cific and more fundamental research will be performed in the next decades (Fig. 21.3). More applied research and site-specific research is currently foreseen after 2050. The current Dutch policy is that a disposal facility should be operational in 2130 (I&E, 2016).

The research for geological disposal of radioactive waste can be subdivided into two main parts. One part studies the feasibility to construct, operate and close an underground facility. The other part assesses the provided safety by a disposal system of engineered and natural barriers after closure.

Geological aspects of subsurface disposal

In the Netherlands two rock types qualify for geological disposal: rock salt and poorly indurated clay both of which have the ability to flow plastically. The low permeability of these rock types (horizontal permeability down to 10^{-19} m²) ensures containment of radionuclides from the waste. Salt is virtually impermeable to oil, gas and water. Potential host rocks considered are the upper Permian (Lopingian) rock-salt formations of the Zechstein Group and Paleogene and Neogene clay formations. Over the last decades, most attention has been given to the Permian Zechstein salt and the Paleogene Boom Member of the Rupel Formation (the Boom Member was previously known as the Rupel Clay Member and is informally known as Boom Clay). A recent study of the Main Rot Evaporite Member concluded that it appears to be locally not well suited for geological disposal, considering current disposal concepts (Altenburg, 2022).

Disposal of radioactive waste in rock salt

Rock salt has multiple advantageous properties and for that reason is considered for the disposal of radioactive waste (e.g. in USA, United Kingdom, Germany, the Netherlands) and hazardous non-radioactive waste (Chandler facility, Australia). Rock salt has an ultra-low permeability (and is essentially impermeable; e.g. Popp et al., 2001), severely limiting any transport of radionuclides to the surface. Rock salt can also deform plastically and restore its ultra-low permeability when disturbed (e.g. Spiers et al., 1986; Urai et al., 2008). Salt creep can slowly surround other materials such as waste to form a tight, essentially impermeable natural barrier (e.g. Hansen et al., 2016). Additionally, there is substantial hands-on experience with construction in rock salt. Salt mining has existed since the Bronze Age (Reschreiter & Kowarik, 2019) and in the Netherlands salt caverns have been constructed for the storage of gas (Zuidwending salt dome,

near Veendam), oil (Marssteden salt dome, Enschede) and nitrogen (Heiligerlee salt dome, near Winschoten). Salt being mined near Enschede using dissolution mining has generated substantial experience with these techniques (Groenenberg et al., 2025, this volume). There is also operational experience with disposal in rock salt: the Waste Isolation Pilot Plant (WIPP) near Carlsbad (New Mexico, USA) has been receiving radioactive waste for disposal since 1999.

Zechstein host rock

Rock salt from the Zechstein Group occurs in large parts of the subsurface of the Netherlands (for more details on Zechstein salt, see Bouroullec & Geel, 2025, this volume; Bouroullec & Ten Veen, 2025, this volume). Two main types of salt formations can be distinguished: bedded and domal salt formations. The characteristics of bedded salt and domal salt are quite different. Due to its uprise, domal salt is relatively pure and homogeneous. The lateral extent of domes is limited (hundreds of metres), and therefore the dome margins are expected to delimit the area useful for a disposal facility. Subrosion by groundwater produces a cap rock at the top of the salt formation and, in some locations, at the margins of the domes. The cap rock may be impermeable or have very low permeability such that it armours the dome against dissolution. Bedded salt is generally less pure than domal salt as it is interbedded with limestone, dolomite, anhydrite, polyhalite and fine-grained siliciclastic beds, which can provide pathways for advective horizontal transport, if reached. Salt beds are typically continuous over large areas.

The Zechstein Group consists of various rock types, including clay, carbonate, anhydrite and rock salt. The spatial distribution of the members containing halite can be consulted online (TNO-GDN, 2023). In the northeastern part of the Netherlands the deposits of the Zechstein Group are present at depths greater than 500 m and reach a thickness of hundreds of metres, mainly due to halokinesis that led to the formation of salt domes and pillars (Fig. 21.4a; Bouroullec & Ten Veen, 2025, this volume). The salt domes can be identified from the thickness map, by assuming a minimum thickness of rock salt in a salt dome of 1300 m.

Salt domes have complex internal geometries and the ductile parts may include brittle inclusions (stringers) consisting of, for example, anhydrite and other impurities such as brine pockets (e.g. Van Gent et al., 2011; Strozyk et al., 2012). The internal structure of salt domes therefore varies and needs to be addressed separately for each individual structure (Geluk, 1998). Several studied salt domes (Harsveldt, 1980, 1986) show the presence of Zechstein Z₂ rock salt in the core and younger (Z₃) salt along the margins, whereas others show an opposite configuration.

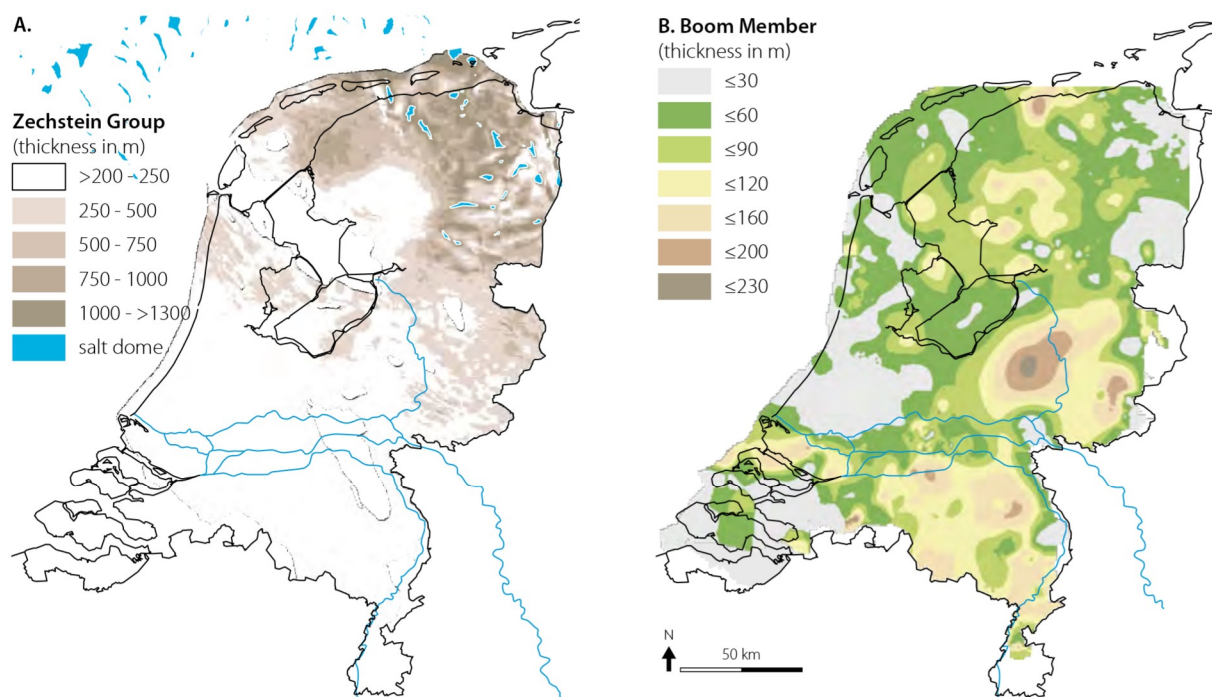


Figure 21.4. a) Onshore thickness of the Zechstein Group (all salt units and associated lithologies combined), displayed where the top of the group is at a depth greater than 500 m below surface (modified from Hart et al., 2015). b) Onshore thickness of the Boom Member of the Rupel Formation (modified from Vis & Verweij, 2014).

Disposal of radioactive waste in clay

Clay-rich formations are considered as potential host rocks for disposal of radioactive waste in numerous countries, including France, Switzerland, Belgium, Canada and Germany (Boisson, 2005). In France, the underground research laboratory (URL) in Jurassic (Callovian-Oxfordian) clay in Bure was declared as a public utility in July 2022. This declaration was necessary to apply for a construction licence for a disposal facility for the high- and long-lived intermediate-level waste. For a site selection in Switzerland, the National Cooperative for the Disposal of Radioactive Waste (NAGRA) investigated three regions of about 10 km², using seismic surveys and deep boreholes. All these regions have Jurassic (Opalinus) clay with a thickness of about 110 m in the subsurface. In 2022, the Nördlich Lägern region in northern Switzerland was proposed for the construction of an underground disposal facility. The construction of an URL to perform further analyses for this disposal facility is currently foreseen in 2034.

Clay formations have favourable properties such as significant lateral continuity, very low permeability, self-sealing of fractures by cementation for indurated clays and self-healing of fractures by swelling of clay minerals for poorly indurated clays, as well as a capacity to chemically retard radionuclide migration. The analysis of fluids contained in clays provides formation-specific properties and evidence of groundwater system stability and resilience to external perturbation through geologic time

(Mazurek et al., 2009). Solute migration is preferentially horizontal due to the lateral continuity in argillaceous sediments. The very low permeability, chemical retardation and self-healing/sealing characteristics contribute to the containment of radionuclides. Examples of hydrothermally formed clays surrounding uranium ores in Canada and Gabon clearly show the effective containment of radionuclides that originated from fission of uranium two billion years ago (e.g. Bentrudi et al., 2011).

Poorly indurated clay – Boom Clay

Poorly indurated clay occurring at relevant depth ranges for a geological disposal facility are known from the Paleogene marine clay layers of the Ieper and Asse members, the Oligocene Boom Member, and from the Neogene marine clay layers of the Breda Subgroup and Oosterhout Formation. Up to now, most attention has been given to the (hydro)geological aspects of the Boom Member.

The clay of the Boom Member ('Boom Clay') is present in almost the entire Dutch subsurface at depths of up to about 1500 m (Fig. 21.5; Vis et al., 2016). In the Netherlands, the Boom Clay has a variable thickness and rarely exceeds 125 m (Fig. 21.4b). As such it is much thinner than the Zechstein rock salt. The Boom Clay is generally thinner than 100 m, but occasionally reaches a thickness of more than 160 m in the Roer Valley Graben in the south and the Central Netherlands Basin in the east of the Netherlands (Fig. 21.4b). In the north, some patches

with a thickness exceeding 120 m are present. Along the south-western and eastern borders of the country the Boom Clay lies at depths of less than ~50 m from surface. Locally it experienced thinning due to erosion associated with Cenozoic uplift during the Pyrenean and Savian inversion phases. Much like rock salt, the clay is not homogeneous and contains both vertical and lateral grain-size changes. In fact, most Boom Clay samples that were analysed for grain size classify as a silt rather than a clay (Vis et al., 2016). The platy form of the clay particles, however, increases the apparent size of the particles with the technique used and, consequently, the clay fraction in the sample is underestimated (Konert & Vandenberghe, 1997).

Facility locality

The host rock is considered to lie at a suitable depth if the effects of any future tectonic processes and climate change are not expected to affect the integrity of an embedded facility for the duration that the HLW will be hazardous. A geological disposal facility will be constructed at a depth of several hundreds of metres, where other rock formations will act as isolating layers.

The maximum depth of a geological disposal facility depends on how the facility is constructed, operated and closed. Many activities may be performed robotically, but involvement of humans is never excluded. As subsurface temperature increases according to the geothermal gradient, a maximum disposal depth of 1000 metres is considered to provide acceptable underground working conditions.

Predicting the future geological development of a facility in a host rock layer requires knowledge of past processes. Given that geological processes occur intermittently or cyclically, the past can be used as a key to the future. For

both rock salt and clay, the research programmes mentioned above have looked at past and future aspects in great detail (e.g. Wildenborg et al., 1990; Remmelts et al., 1993; Ten Veen et al., 2015). We will elaborate on some of these aspects below.

Glaciation

The latitudinal position of the Netherlands makes it susceptible for glaciations as has been extensively documented for the Quaternary (see Busschers et al., 2025, this volume). The geological record of the past half a million years shows that the north of the Netherlands has been impacted more by glaciations than the south. The ice sheets during the Elsterian, Saalian and Weichselian never reached the southern provinces of the country (Westerhoff et al., 2003b; Ten Veen et al., 2015). During the retreat of the Elsterian ice sheet, subglacial erosion scoured sediments up to 600 metres deep in the northern Netherlands (Fig. 21.6a; Keller, 2009; Stackebrandt, 2009; Ten Veen et al., 2015). Glacial basins from the Saalian glaciation are however rarely deeper than 150 metres (Van Dijke & Veldkamp, 1996).

An ice sheet would not only have erosional effects, its physical load also impacts radionuclides released from the engineered barrier system to the host rock. In the case of a clay host rock and an assumed ice-sheet thickness of 1000 metres, the ice load presses the pore water out of the clay (Wildenborg et al., 2000). A recent study estimates that the ice-sheet thickness was around 200 metres in the northern Netherlands during the Saalian glaciation (Ten Veen et al., 2015). Consequently, the ice loading effect is expected to be less than previously assumed (Wildenborg et al., 2000), reducing the rate of enhanced radionuclide transport through clay by a factor of five. Ironically, current global warming may 'postpone' the next glaciation by

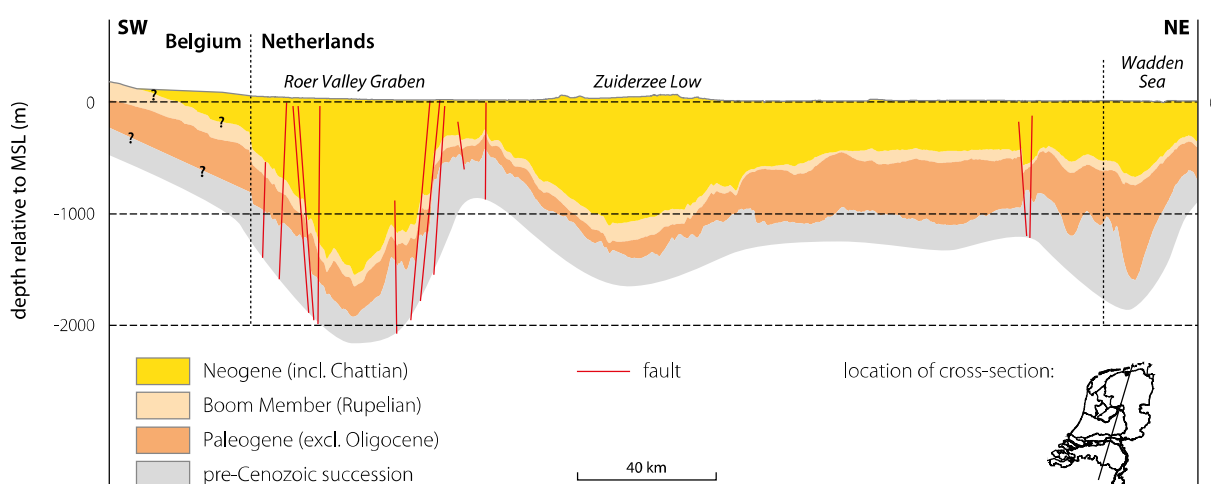


Figure 21.5. Cross-section showing the variable depth of the Boom Member in the Netherlands and the cropping out of this clay in Belgium. The absence of faults in the Zuiderzee Low area probably reflects a lack of data (modified from Vis et al., 2016).

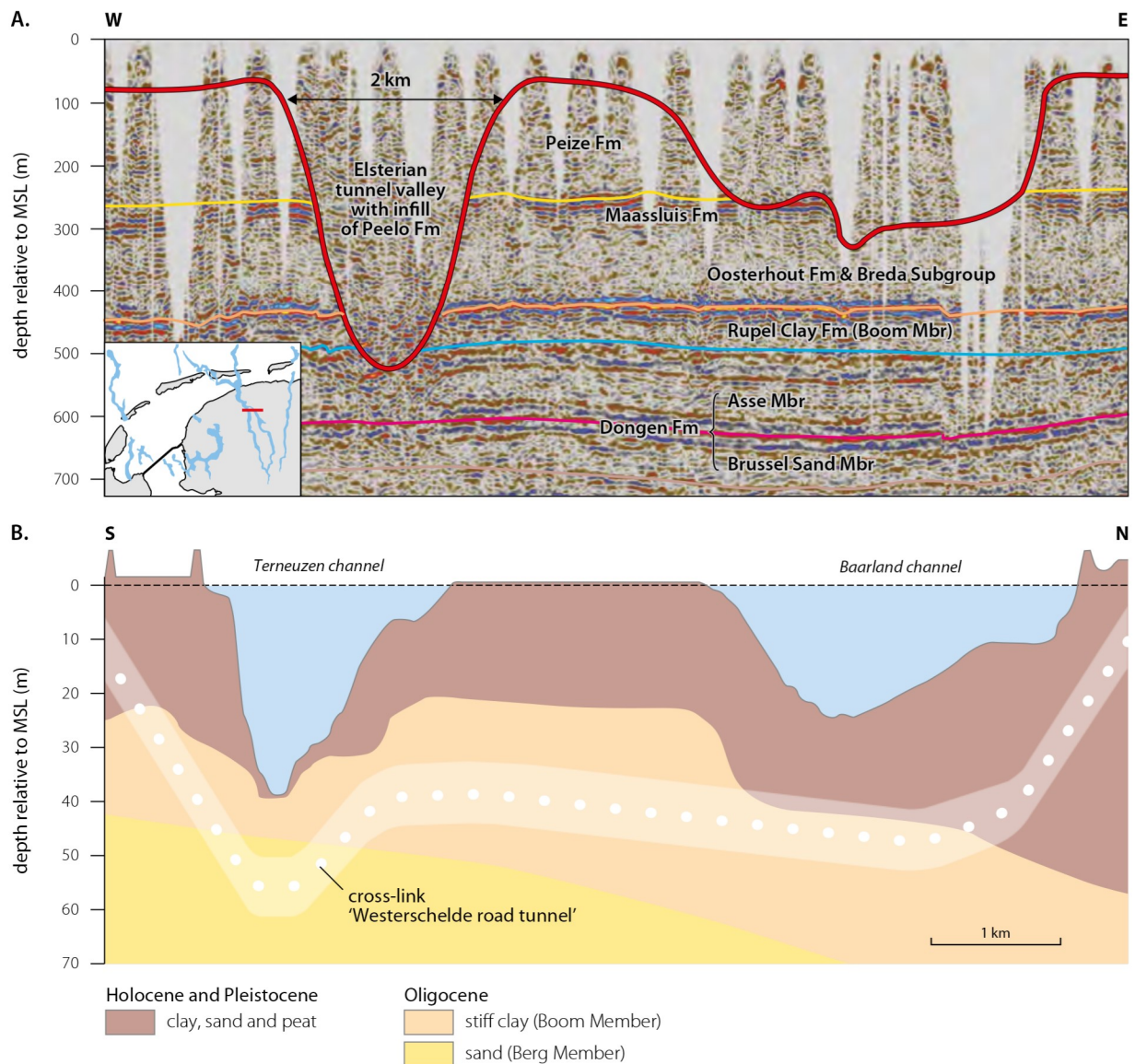


Figure 21.6. a) Erosion down to the Boom Member by tunnel valleys from the Elsterian ice age in the north of the Netherlands (modified from Ten Veen et al., 2015). See inset map for location of tunnel valleys and seismic section. b) Erosion by tidal channels in the southwest of the Netherlands (modified from De Mulder & Ritsema, 2003). Note that the Westerschelde road tunnel is constructed in the clay of the Boom Member.

more than 100,000 years (Ganopolski et al., 2016) such that glacial loading and erosion becomes a negligible hazard for some types of waste such as vitrified HLW. That is the case because this type of waste reaches a radiotoxicity smaller than uranium ore by decay after 20,000 years (Gruppelaar et al., 1998).

The current long-term research programme proposes a minimum disposal depth of 200 metres for the geological isolation of radioactive waste. In the case of a future glaciation which does not result in ice sheet expansion across the Netherlands, permafrost formation is a process that could be expected. Based on a modelling study, the maximum depth penetration of permafrost is expected to range

between 140 and 185 metres in the Netherlands (Ten Veen et al., 2015), which is not in the range of the proposed disposal depth.

Channel incision

Incision by tidal channels in which much flow energy is concentrated in a narrow zone is the most powerful type of non-glacial vertical erosion below sea level. Modern examples include the Holocene tidal channels of the 'Pas van Terneuzen' and 'Everingen' (Westerhoff et al., 2003a) in the southwest of the Netherlands (Fig. 21.6b). These channels are up to 100 metres deep and have eroded down into the Boom Clay. The difference in depth between subglacial

erosion in the north (up to 600 metres) and tidal channel erosion in the southwest (up to 100 metres), illustrates that suitable disposal depths may differ geographically.

Tectonics

Tectonic processes can affect a geological disposal facility by lifting up its embedding geological layer so much that it gets exposed at the surface, or by hydrological changes affecting fluid flow (Ten Veen et al., 2015). Based on the known pace of tectonic movements in the Netherlands in the past, it is unlikely that exposure of a facility will occur during the next million years (Ten Veen et al., 2015). Tectonic processes and related seismicity can have an effect due to possible changes in groundwater flow patterns through faults and fractures. Fault activity can also be enhanced by loading and unloading of the lithosphere by sediment, water or ice (Ten Veen et al., 2015). Especially differential loading by sediment and ice has been the topic of study in the OPLA-programme related to rock salt (Remmelts et al., 1993).

Hydrology and geochemistry

In natural geological processes, groundwater flow and geochemistry play an important role during burial and diagenesis. As any geological disposal facility is constructed in geological layers that have been affected by these processes for millions of years, any human intervention is expected to have an impact on the natural conditions. After permanent closure of a facility natural processes will take over again and, after a certain period, radionuclides will be released from the engineered barrier. Ideally, the host rock will isolate the disposal facility in such a way that radionuclides will either not escape the host rock at all or only after a delayed period. Due to its physical characteristics, clay has the advantage of being able to geochemically react with radionuclides. For details on recent work on these topics, the reader is referred to recent reports from the Dutch OPERA-programme (Vis & Verweij, 2014; Hart et al., 2015; Griffioen et al., 2017) or studies on the Opalinus Clay in Switzerland (e.g. Bradbury & Baeyens, 2011).

Disposal of radioactive waste in rock salt

Disposal concept for a facility in rock salt

The disposal concept describes how to construct, operate and close a disposal facility. Several disposal concepts have been developed for rock salt (e.g. Hamstra, 1981; Poley, 1999; Grupa & Houkema, 2000). In the most recent concept (Bartol et al., in preparation), it is assumed that a geological disposal facility is constructed in the core of a salt dome belonging to the Zechstein Group (Fig. 21.7). While

this concept is for domal salt, this does not exclude a disposal facility in bedded salt.

Construction and operation of the geological disposal facility in rock salt

Within the salt dome, a two-level geological disposal facility is envisaged (Fig. 21.7a), connected to the surface by two vertical shafts. The upper level of the geological disposal facility will be constructed at a depth of at least 750 metres below the surface, i.e. below the observed maximum depth of subglacial erosion. Construction will be done using modern non-explosive mining techniques such as for example a drum miner. The upper level will be used for the disposal of LILW (Fig. 21.7b). For emplacement within the disposal rooms, well-established technologies will be used, similar to the way waste is currently handled and stored at COVRA. Depending on the type of waste, packages will either be placed horizontally in racks (waste in 200 litre drums) or placed on the ground (waste in 1000 litre containers or in Konrad Type II containers) using (heavy) forklift trucks (Fig. 21.7d).

After all waste has been placed within a disposal room, optionally bags containing MgO may be placed next to and on top of the waste packages in order to absorb CO₂ released by decaying organic components in the waste. Open spaces in salt will be constructed sufficiently large to account for salt creep that can be in the order of a few mm per year.

The lower level of the disposal facility at a depth of 850 metres below the surface will contain the HLW (Fig. 21.7c). The construction method will be similar to the upper level. In the most recent disposal concept (Bartol et al., in preparation), HLW will be placed in a single (standardized) overpack at the surface that provides both containment and shielding. Within the geological disposal facility, these overpacks are placed in shallow vertical holes (Fig. 21.7d) half the height of the overpack that should prevent their tipping and consequential damaging. Since an overpack provides shielding, no additional radiation protection is needed within the geological disposal facility. This makes the handling of the overpack within a geological disposal facility easier as it is possible to stand next to it. A disadvantage of using an overpack is that heavy equipment is required for their emplacement. Rather than constructing all the disposal galleries at once, new disposal galleries will be constructed at the time the 'old' disposal galleries have been fully filled. The rock salt removed during the construction of the new galleries will then be used to backfill galleries already filled with waste. There is broad experience and knowledge on the use of granular salt as backfill (e.g. Spiers et al., 1988; Poley, 2000). Seals will be constructed at both ends of a backfilled disposal gallery.

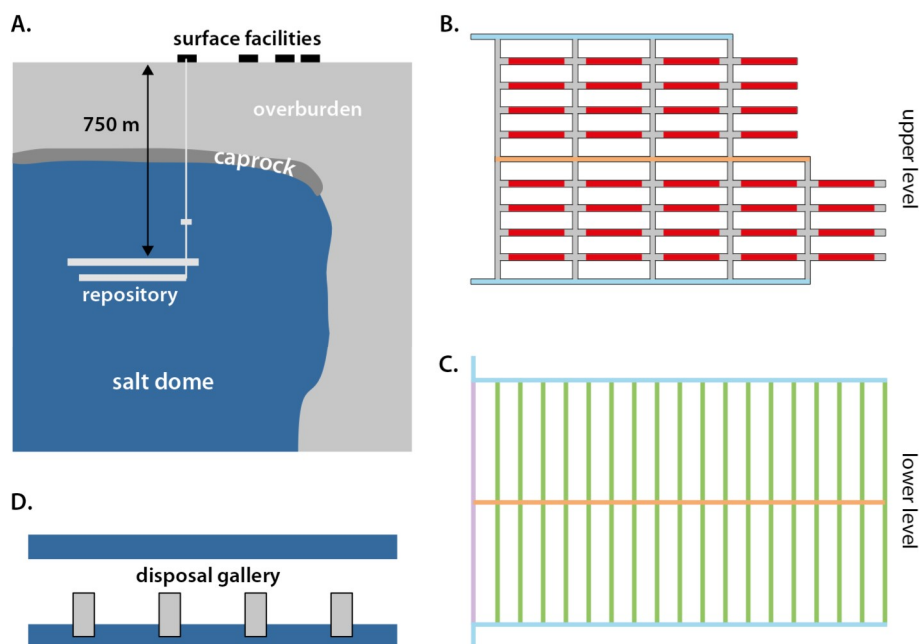


Figure 21.7. a) Schematic cross section through a salt dome, showing a geological disposal facility with two vertical shafts connecting the facility to the surface. b) Plan view of the upper level consisting of disposal rooms (red), a transport tunnel (orange) and ventilation tunnels (light blue). c) Plan view of the lower level consisting of a central transport tunnel (orange), ventilation tunnels (light blue), service tunnel (light purple) and the disposal galleries (green). d) Cross section through a disposal gallery in which waste is emplaced. Grey: standardized overpack, blue: rock salt. None of the figures are at scale.

In the case that HLW needs to be retrieved, the seal and backfill will need to be removed using light machinery or manual mining techniques to avoid damage of the overpacks. Geophysical techniques such as radar could be used to locate overpacks within the backfill (Anonymous, 1986).

Closure of the geological disposal facility in rock salt

At the end of the operational phase, the geological disposal facility will be permanently closed and all the remaining open spaces will be backfilled using granular rock salt. By doing so, no further maintenance of the geological disposal facility will be required as the geological disposal facility provides safety in a completely passive manner. Seals will be placed in the shafts connecting the geological disposal facility with the surface. These seals will likely not only consist of granular rock salt but of a combination of different materials, such as salt and concrete, with each material providing its own water tightness but at different time scales (Bollingerfehr et al., 2013).

Disposal system with rock salt

For the long term evolution of the disposal system in rock salt, both normal and altered scenarios are considered. The normal evolution scenario (Verhoef et al., 2017), in which the degradation of the container and the effects of climate change evolve as expected, is the most likely. The

altered evolution refers to one in which either the geological disposal facility is abandoned during the operational phase, during intensified glaciation or unintentional human intrusion takes place (Verhoef et al., 2017). Here we only discuss the normal evolution and unintentional human intrusion.

Normal evolution

In the normal evolution scenario of the disposal system, the engineered barriers (overpacks and seals) will initially provide containment. Over a period of less than 10^3 years, these barriers will degrade and lose their containment function. Concurrently, the backfill with its ultra-low permeability will take over the containment function of the engineered barriers. In the normal evolution, the waste and therefore the radionuclides are effectively trapped within rock salt for a period of $<10^5$ years. It is only at longer geological time scales ($>10^5$ years) that geological processes such as subrosion and diapirism could result in the release of radionuclides into the biosphere. While both processes could result in the release of radionuclides, they will not necessarily affect the safety of the disposal system as these processes are expected to be very slow. Hence, it is expected that it will take more than 10^6 years before any release is expected due to subrosion and diapirism. By that time, the hazardous potential of the waste will have diminished significantly. The process of subrosion may lead

to salt dissolution by groundwater flow around and over a salt dome and in this case the natural barrier function will be reduced. Subrosion could eventually result in the total destruction of the natural barrier and consequently the release of radionuclides into the groundwater. When released, these radionuclides will gradually move upward with the groundwater through the subsurface and could eventually reach the surface and enter rivers, lakes and wells. In this scenario, humans could become exposed to the radionuclides in various ways, for example, through drinking water from contaminated wells or by using contaminated ground- or river water for the irrigation of crops.

Diapirism is the upward movement of salt with respect to the mother (bedded) salt layer (Hudec & Jackson, 2007). In case the upward moving salt contains a geological disposal facility, the travel time that radionuclides need to reach the surface will decrease. Over very long time-scales, diapirism could even bring the radioactive waste mingled in salt to the surface (Prij et al., 1993). Salt domes piercing the surface are well known from Iran (e.g. Waltham, 2008), but also occur in the North Sea in block K9 (Laban, 2010). If a repository is brought to the surface by diapirism, exposure to humans may occur by direct radiation and inhalation of contaminated dust.

Both subrosion and diapirism rates vary between salt domes, within a single salt dome and also with time. Diapirism rates are high during periods of tectonic activity (Hudec & Jackson, 2007) while subrosion rates can increase during periods of glaciation (Geluk et al., 1993). Overall, the subrosion rates vary between 0.1 and 1.0 mm/year (Zirngast, 1996; Köthe et al., 2007; Lauwerier, 2022) while diapirism rates vary between 0.01 and 0.1 mm/year (Zirngast, 1996; Köthe et al., 2007; De Gans & Duin, 2010; Lauwerier, 2022). If a relatively high subrosion rate of 1 mm/year is assumed (Köthe et al., 2007; Lauwerier, 2022) and if there are 200 metres of salt between the repository and the overburden, it will take about 200,000 years before radionuclides would be released into the groundwater. If a disposal facility is built at a depth of 850 metres (Bartol et al., in preparation) and a high diapirism rate of 0.5 mm/year is assumed, it will take about 1.7 million years before the facility reaches the surface. In both cases the radioactivity of the waste will have decreased significantly due to natural decay by the time any of the material reaches the biosphere. The waste will have a lower level of radiotoxicity than uranium ore.

In reality a combination of different processes and their interactions should be considered. For example, in a scenario that combines subrosion and diapirism (diapirism-subrosion scenario), subrosion will diminish the salt barrier around the waste, while at the same time the salt dome moves upwards gradually, reducing the travel

time of the radionuclides to the surface. As the radioactivity level of waste decays over time, the combination of subrosion and diapirism probably does not pose a problem.

Unintentional human intrusion

Special attention needs to be given to human intrusion and, specifically to inadvertent human intrusion, as salt is currently considered a resource and is used for storage of, for example, gas and nitrogen. It is unlikely that in the near future unintentional human intrusion will occur since the location and content of a geological disposal facility are always registered.

In the far future, inadvertent human intrusion in a geological disposal facility constructed in a salt dome could happen, for example during the construction of a cavern for gas storage. It could also happen for a geological disposal facility built in a bedded salt formation when exploration boreholes are drilled through the same formation. While inadvertent human intrusion cannot be excluded, it is possible to either reduce the consequences or reduce the probability of occurrence (Mobbs, 2012). For the disposal concept discussed here (Bartol et al., in preparation), a two-level geological disposal facility design was selected. Having a two-level geological disposal facility minimizes its footprint and thus decreases the probability of human intrusion. Also, cuttings are currently examined during drilling. If this is also done in the future, workers will be warned as they may encounter material from the upper level of the facility containing lower level waste. Other measures that could be taken are the erection of monuments on the surface or subsurface markers like steel or concrete slabs buried just above the salt dome to indicate that there is a geological disposal facility below the surface (Mobbs, 2012). For the WIPP facility in the USA, such warning signs and surface markers have been suggested (Trauth et al., 1993).

Disposal of radioactive waste in poorly indurated clay

Disposal concept for a facility in poorly indurated clay

The disposal concept developed in OPERA has recently been updated (Fig. 21.8) for the inventory of waste collected until 2130 (Burggraaff et al., 2022). In this concept (scenario 1), all types of waste are placed at the same depth. The eventual design of the facility will be determined by the characteristics of the site. For example, if multiple stacked clay formations are present, the deeper one could be used for waste packages of HLW and the shallower ones for lower level waste. Due to the geometry of clay layers (i.e. large lateral extent and relatively limited

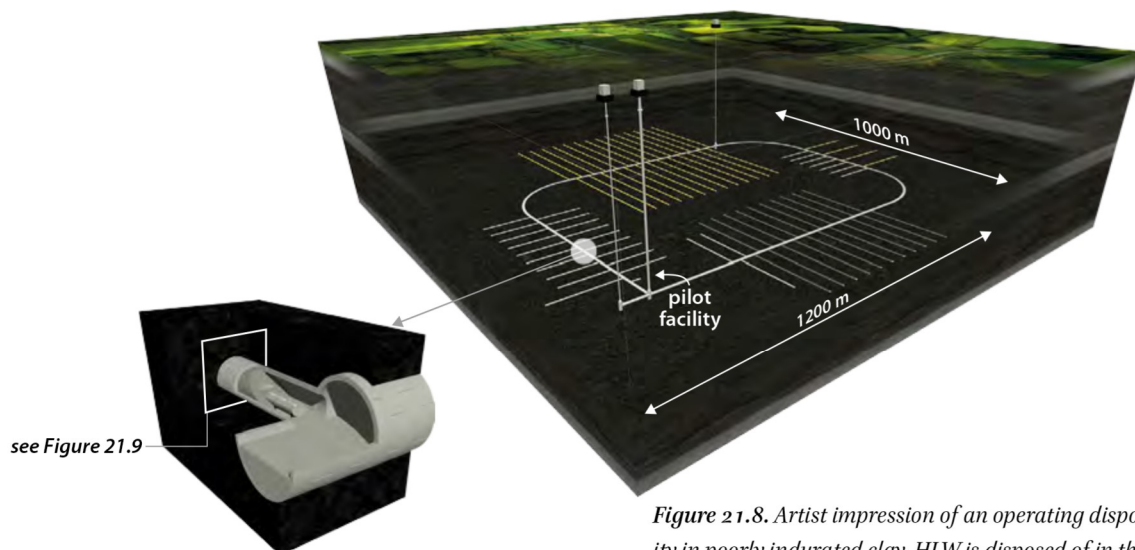


Figure 21.8. Artist impression of an operating disposal facility in poorly indurated clay. HLW is disposed of in the section with short tunnels (pilot facility). LILW is disposed of in the other three sections. Illustration: COVRA.

thickness), galleries will be constructed horizontally, also to minimize vertical disturbance of the clay layer.

Before the operational phase commences, a pilot facility is envisaged which consists of a comparable layout to that proposed for disposal of HLW but containing only a single HLW package. This facility will be equipped with multiple sensors to monitor the impact of the waste package on the behaviour of the engineered barriers and on the in-situ host-rock conditions. The pilot facility will be open to the public.

Construction of the geological disposal facility in poorly indurated clay

Two shafts will connect surface facilities with the underground facility (Fig. 21.8). They will ensure the circulation of fresh air through the facility. The additional rescue shaft has a smaller diameter. The construction will use proven technology such as a tunnel boring machine (TBM) that uses concrete segments to prevent tunnel collapse. This technique was used for the Westerschelde tunnel (Fig. 21.6b) and for constructing the underground facility in the Boom Clay in Mol (Belgium) at 225 m depth (EURIDICE). The number of transport tunnels, their connections with each other and the length of disposal galleries will be continuously updated by assessing the impact of operational events or hazards such as vehicle fire.

The construction of an underground facility requires knowledge about the geotechnical properties of the poorly indurated clay at depth. This knowledge is scarce. For research into the technical feasibility as well as post-closure safety, experiments with clay host rock material are required. Sediment cores of indurated clays are available at the TNO core storage in Zeist (e.g. Koenen & Griffioen,

2014). However, these samples are stored under ordinary air and dry conditions. The clays undergo so-called core shed diagenesis (such as drying and cracking, alteration of minerals and precipitation of salts) that alters their initial state and makes them less suitable for specific studies of the clay. Rather, geotechnical properties are determined from freshly cored and well-preserved clay. To date, experimental work on freshly cored clay is limited to the Boom Clay taken from the town of Blija in 1998 (e.g. Barnichon et al., 2000), the town of Borsele in 2011 (e.g. Behrends et al., 2015) and from the city of Delft in 2022 (Vardon et al., 2022).

Operation of the geological disposal facility in poorly indurated clay

For safety reasons, the civil engineering activities for constructing the facility need to be separated from the radiologically controlled activities. The construction of a facility at a single depth should be completed before emplacement of the waste packages starts.

During the operational phase, the methodology for waste package emplacement strongly depends on the ionising radiation at the surface of the package and also on the mass and dimensions of the package. The largest volume of waste stored at COVRA's premises is packaged in such a way that a worker can handle it without additional shielding. This waste is handled in the storage facilities using electric forklift trucks. A similar handling methodology is foreseen for the emplacement of waste packages in future disposal galleries.

Excavating the tunnels causes damage to the host rock. When using tunnel boring machines and concrete liners, the clay is shielded from activities during the operational

phase. Associated ventilation is expected to have no impact on clay properties and drying out and fracturing by shrinkage will be limited.

The construction of a gallery raises the hydraulic conductivity in the vicinity of the tunnel and causes pore water pressure to decrease. The extent of the increase of the conductivity depends on the diameter of the gallery, the overcut used for the excavation and time. After a few months, the conductivity in Boom Clay at 1.5 metres from the interface between concrete and clay for a gallery with a diameter of 4.6 metre was measured to be less than three times the virgin hydraulic conductivity (Bernier et al., 2007). After 8 years at the same position, this conductivity was measured to be less than two times this virgin conductivity (Berckmans et al., 2013). Measurements of the conductivity near the interface between concrete and clay have shown to be similar to conductivities further away from this interface for a smaller gallery (Dizier et al., 2017). Consequently, a hydraulic conductivity equal to the virgin clay host rock may be assumed from the start of the post-closure phase everywhere in the clay formation if an appropriate construction technique is used and the diameter of the disposal gallery is limited.

Closure of the geological disposal facility in poorly indurated clay

A stepwise closure of the disposal facility is foreseen. Galleries in which the emplacement of waste is completed will be backfilled with a material that can be easily removed in order to facilitate the retrieval of a waste package should this be necessary. Foamed concrete has been proposed as a backfill (Verhoef et al., 2014) and studied in detail (Mladenovic et al., 2019). Further closure of the disposal facility should prevent the shafts and ramp from acting as preferential pathways for radionuclide transport in the post-closure phase. The transport galleries would be backfilled with a mixture of excavated clay and grout to mitigate the acidification by oxidation of pyrite within the clay. Most lining material from the underground facility towards the surface would be removed.

Disposal system with poorly indurated clay

After closure of the geological disposal facility, the engineered barriers and the host rock contribute to containment of radionuclides. Many engineered barriers in this disposal system are composed of cementitious materials, manufactured with transport properties that are lower than those in the clay host rock. This limits preferential pathways for radionuclide transport to the host rock itself or to interfaces. After closure, joints between concrete segments are expected to be the preferential pathways for radionuclides into the clay host rock as well as the preferential paths for ingress of clay pore water into the

facility (Neeft et al., 2019). The natural barriers are the poorly indurated clay formation and the surrounding rock formations. The low hydraulic conductivity of the clay contributes to the containment of radionuclides. In view of the saline groundwater conditions at disposal depths, the dominant retardation process of radionuclides in the clay needs to be assessed.

Characteristics of natural barriers in the disposal system

In general, there are two transport mechanisms in clay: diffusion and flow. Diffusion is driven by the concentration gradient of the diffusing ions, while flow is driven by a pressure gradient and requires permeability (Hasenpatt et al., 1989). The permeability of plastic clay decreases with increased loading (Wildenborg et al., 2000). In an experiment introducing a load equivalent to 500 metres burial depth, a permeability value of $1.65 \times 10^{-19} \text{ m}^2$ was measured from a core of Boom Clay (Harrington et al., 2017). This permeability value is so low that pore water can be assumed to be stagnant and transport will be diffusion-dominated.

Radionuclides can be prevented from migrating by retardation. This can take place through co-precipitation and chemisorption. Co-precipitation is the simultaneous precipitation of a radionuclide with non-radioactive isotopes of the same element or different elements. An example is the precipitation of carbonates with calcium and uranium. Co-precipitation is a poorly investigated process in clay barriers. Chemisorption is a kind of adsorption that involves a chemical reaction between the surface and the adsorbate and is considered to be the main retardation mechanism in studies performed on Boom Clay from the Belgian research facility in Mol (due to the bicarbonate (HCO_3^-) type of water (De Craen et al., 2004; Bruggeman & Maes, 2017). Because the pore water chemistry is more saline in Paleogene clay host rocks in the Netherlands, the effectiveness of chemisorption as a retardation mechanism may be different from the Belgian example.

The migration of radionuclides in the clay host rock can be investigated by studying past migration of natural radionuclides and non-radioactive analogues or by using artificial radionuclides. Chemical interactions between engineered barriers such as concrete and clay host rock are expected to have a negligible impact on migration.

Evolution of a disposal cell with vitrified HLW

Setting up future evolution scenarios of disposal cells provides insight into the long-term processes that are likely to occur. For an example a cell with vitrified HLW with a highly insoluble waste matrix is used (Fig. 21.9). Initially all the engineered barriers are undamaged (Fig. 21.9a). A carbon steel overpack surrounds the waste package and

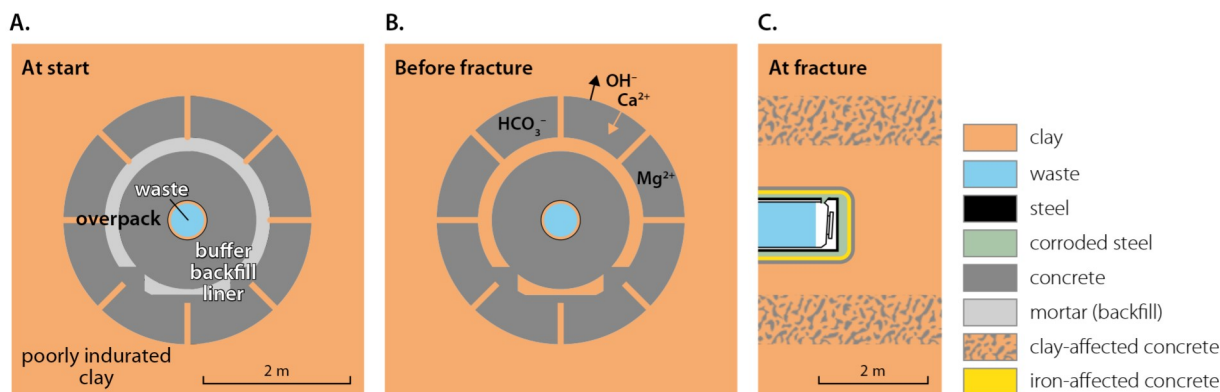


Figure 21.9. a) Cross section through a closed horizontal disposal gallery in clay with emplaced high-level waste at the start of the post-closure phase. b) After some time when no fracturing of engineered barriers has occurred. c) Longitudinal section of this disposal gallery after fracturing of the overpack. Note that the scale in (a) and (b) is different than in (c).

prevents contact between the waste and pore water. The surrounding concrete buffer limits corrosion of the carbon steel overpack by ensuring a high pH, chemically reducing conditions and a limited diffusion of soluble iron. The cementitious backfill (mortar) eliminates the void volume within the disposal cell for sufficient heat dissipation. The concrete segments of the disposal gallery limit the ingress of clay pore water during the initial post-closure phase.

During the first 100 years after closure, the temperature at the interface between waste and steel is calculated to be in the range of 80°C to 94°C, but the temperature of the host rock at the outer interface of the concrete segments remains below 50°C. After 1500 years, the temperature of the host rock will have cooled down to virgin conditions (Neeft et al., 2019). Oxygen from air trapped in the disposal cell will be consumed by corrosion of steel and concrete. Additionally, anaerobic corrosion of the carbon steel overpack takes place (Fig. 21.9b). Archeological analogues of man-made steel or iron embedded in soil or water indicate that anaerobic corrosion rates of steel are at least 100 times lower than aerobic corrosion rates (Crossland, 2005). Over time, the concrete in the vicinity of the (corroding) steel alters by uptake of (dissolved) iron, forming a 'loosely bound material' (Atkins et al., 1991).

The penetration of solutes from the clay pore water also alters the concrete. Magnesium, sulphate, chloride and bicarbonate ions from the pore water will react with the minerals in the cementitious materials. A progressive degradation of concrete is expected (e.g. Atkinson et al., 1985; Dauzères, 2016). The unaffected parts of the concrete have a high pH and will still have sufficient strength to prevent deformation. After several thousands of years, when the waste no longer heats the host rock, the combination of the lithostatic pressure on the engineered barrier system, the loss in thickness of the carbon steel overpack and the

reduction in thickness of the concrete will lead to fracturing of the steel overpack (Fig. 21.9c).

Fracturing allows for contact between pore water and vitrified HLW and will generate a siliceous hydration zone and products precipitating on top of this zone. The alteration mechanisms of vitrified waste are expected to be the same as for basaltic glass (a natural volcanic glass) except that the precipitated product is named palagonite. This is a mixture of clay minerals and zeolites. Palagonite occurs as rims of varying thickness around glass fragments (Lutze et al., 1987). Chemisorption of remaining radionuclides takes place through these precipitated products. The glass alteration is therefore anticipated to have a very small impact on the potential release of radionuclides such as uranium, plutonium and americium (Van Iseghem et al., 1992). An example of a radionuclide that will be released during glass alteration is ^{79}Se . The alteration rates of basaltic glass have been estimated to be 0.1 μm per 1000 years (Lutze et al., 1987). The half-life of ^{79}Se is 327,000 years. Consequently, most of the remaining ^{79}Se is expected to decay within the vitrified waste form and will not be released to the surroundings.

The description of the future evolution of a disposal cell containing vitrified HLW illustrates that processes having an impact on the clay host rock are likely to be limited to minor alteration of the host rock in the vicinity of the disposal facility.

Outlook

Dutch policy aims for radioactive waste to be disposed of in an underground facility by the year 2130 (Fig. 21.3). The timeline for geological disposal of radioactive waste in the Netherlands considers changes in the type and

amount of radioactive waste and progress in the knowledge on how to construct and operate disposal facilities. The timeline (Fig. 21.3) is updated every 5-10 years, thereby taking new developments into account. The global political situation and (foreign) experience on the generation of radioactive waste and its disposal influence national public acceptance of modes of disposal. Changing public attitudes will impact the timeline and associated activities. In the Netherlands small but continuous financial resources are available for research into disposal of radioactive waste. This research is used for well-informed adjustments to the timeline. The resources are also used to inform the general public about the current state-of-the art of waste disposal.

The decision-making process for an underground facility requires information on the host-rock formations. In future, such information will be collected from boreholes drilled in the area of selected sites. Until then, COVRA participates in scientific drilling activities in the Netherlands to obtain non-site specific information for a safety case of disposal of radioactive waste in clay. For a disposal facility in salt, the main focus for the near future will be on fundamental research, including the understanding of the long-term evolution of the disposal system with the host rock. In the far future, the focus will shift towards applied research that would, for example, include a more in-depth study of salt domes and bedded salt in the Netherlands.

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Digital map data

Spatial data of figures in this chapter for use in geographical information systems can be downloaded here:
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