SUMMARY

COPERA CLAY 2024

A CONDITIONAL SAFETY CASE AND FEASIBILITY STUDY

Date: November 2024
Compilers: Neeft, Vuorio, Bartol, Verhoef, McCombie, Chapman

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Summary

The principal objective of this report is to present an overview of the results and conclusions of the on-going work in the Netherlands on developing safety cases for a Geological Disposal Facility (GDF) in poorly indurated clay. The work is part of COVRA's broader COPERA programme, which is envisaged to run for decades and which also includes research on a GDF in rock salt and on multinational solutions. The structure of our long-term research programme can be used for several programming periods, and each decade will result in an iteration of two safety cases, one for a GDF in clay and one for a GDF in salt. The implementation of the European Directive on radioactive waste management requires an evaluation of the national programme every decade. The last Dutch national programme was published in 2016 and is currently being evaluated. A revision of the national programme needs to be completed in 2025. The safety cases for GDFs in clay and rock salt have been developed as input for this evaluation.

This safety case for a GDF in Paleogene clay updates and expands the OPERA (2017) clay safety case, taking into account progress in the Netherlands and elsewhere in the intervening years. The present COPERA(2024) safety case is less comprehensive than many other safety cases but wider in scope. The progress made in clay studies is mostly related to improved understanding of the physical and chemical processes involved in determining the safety of the multibarrier system with natural and engineered barriers. However, significant effort has also been put into examining more closely the practicability and efficiency of construction and operation of a GDF; this explains why the present report title refers to both safety and feasibility. Our intent is to ensure that the report can be read as a stand-alone document, and this means that information that remains the same as in the 2017 OPERA Safety Case has been brought forward from that report, amended with updated information only as necessary.

The present report is a scientific/technical document, describing engineering and geological requirements needed to assure that a safe GDF can be implemented in the Netherlands. We are, however, fully aware that a successful GDF programme must address both societal and technical issues. Globally, the greatest obstacles to geological disposal of waste have been those related to achieving sufficient public and political support for the concept itself and, most specifically, for siting work, including exploratory drilling. The Rathenau Institute is currently looking at a societally based approach to identifying possible siting areas and locations for a GDF. Information from their reports has been included in this safety case.

What is new or different from OPERA

Apart from Boom Clay, other Paleogene clay formations are also considered. This increases the range of potential siting regions that might be available in the Netherlands and implies that alternative disposal facility designs become feasible, including a multi-level option in which the types of waste can be disposed of according to their hazard potential.

Changes in design have been made in order to improve the practicality of the system for emplacement of waste packages in the GDF. In addition, radiation protection calculations have been initiated to demonstrate that operational safety can be provided.

Good quality Paleogene (Ypresian and Landen) clay borehole cores have now been obtained at a depth of about 400 m in Delft.

The safety case is being progressively interfaced with the Requirements Management System (RMS) that COVRA is developing; this will structure all of its activities from waste conditioning, through temporary waste storage to disposal operations, including ensuring that safety is provided after closure of the GDF. Further levels are defined, taking into account the need to be compatible with the parallel safety case in salt, and also with COVRA's waste storage programme.

The cost estimate has been updated with the waste inventory for Waste Scenario 1, made in 2022 in the framework of the national programme. In addition, new packaging assumptions have resulted in a significant decrease in the space required for disposal of some wastes.

Experimental measurements, especially with Paleogene clays and disposal representative concrete materials, have been analysed to provide some validation of the models and data used in the safety assessment.

Previous Dutch national disposal programmes OPLA, CORA and OPERA were all prepared at the conclusion of specific programmes with defined durations. COPERA is COVRA's on-going programme that will allow incorporation of recent foreign achievements in the prioritization for research into disposal of waste in the Netherlands, enhance national initiatives and support Dutch researchers working in international collaborations such as EURAD, in which 23 EU Member States develop the knowledge base for disposal of waste.

Introduction

Nuclear technologies are used in electricity generation, medicine, industry, agriculture, research and education. These technologies generate radioactive wastes that must be managed in a way that ensures safety and security at all times. For materials that remain hazardous for thousands to hundreds of thousands of years, the acknowledged approach to long-term isolation and containment is emplacement in a GDF in a stable geological environment beneath Earth's surface, and closing and sealing this GDF.

The Netherlands, along with other countries with significant quantities of long-lived radioactive wastes, has chosen geological disposal as the official national policy. The reference date for implementing a national GDF is around 2130, slightly more than 100 years from now. The extended timescale allow flexibility, in case options other than disposal in a national GDF become available, such as disposal of Dutch waste in a shared, multinational GDF.

COPERA is COVRA's on-going programme that started in 2020. It includes novel elements relative to the previous national programmes, OPLA (1993), CORA (2001) and OPERA(2017).

The main thrust of this COPERA Safety Case is to provide an overview of the arguments and evidence that can lead to enhancing technical and public confidence in the levels of safety achievable in an appropriately designed and located GDF. It addresses three important objectives:

- **Increase technical, public and political confidence** in the feasibility of establishing a safe GDF in the Netherlands.
- **Enhance the knowledge base in the Netherlands** related to geological disposal.
- **Guide future work** in the research for geological disposal of waste in the Netherlands.

The development of scientific and technical understanding, data and arguments that support the Safety Case has been structured by addressing specific research questions using a multidisciplinary approach, covering many areas of expertise.

How much waste is destined for disposal?

Three waste generation scenarios were made in 2022 in the framework of the national programme. Waste Scenario 1 is the same as that used in OPERA: Operation of Borssele Nuclear Power Plant until 2033 and replacement of the High Flux Reactor in Petten by Pallas. The expected eventual inventory of wastes from all sources that is destined for geological disposal is summarised below.
The design of the GDF in clay host rock can be easily extended with the other two Waste Scenarios, provided that the waste characteristics are the same as those used for Waste Scenario 1.

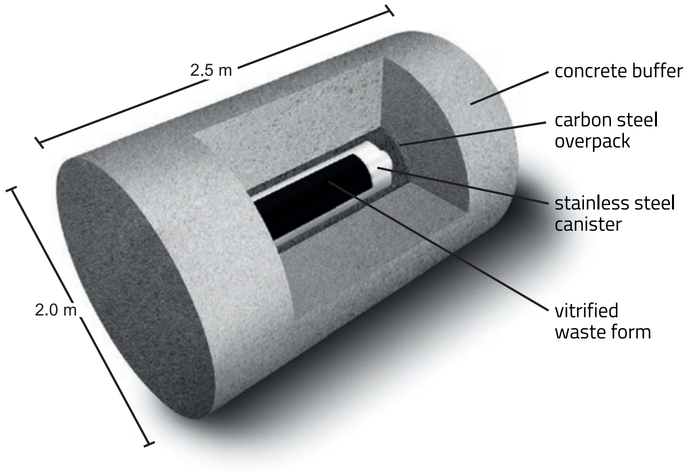
Waste Category	In storage		Packaged for disposal		
	Volume [m³]	Number of canisters / containers	Number of packages	Volume [m³]	Weight per package [tonne]
Spent research reactor fuel	49	244	244	1840	20
Vitrified HLW (vHLW)	86	478	478	3754	22
Compacted hulls & ends (Non heat generating HLW)	90	502	72	452	20
Dismantling waste (LILW)	3814	-	826	3814	Max 20
TE-NORM (LILW)	49360	-	12600	58070	Max 20
Processed LILW	31461	108400	108400	31461	Max 3

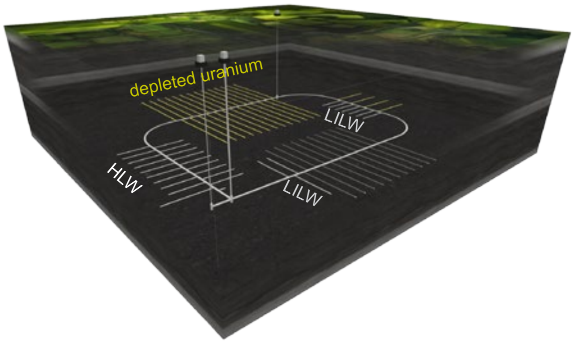
HLW = High Level Waste; LILW = Low and Intermediate Level Waste

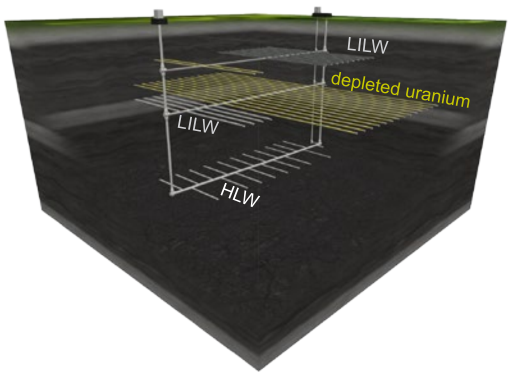
What could a Dutch a geological disposal facility look like?

The GDF design is based on the universally adopted ‘multibarrier system’ concept of natural and engineered barriers that contain and isolate the wastes and prevent, reduce or delay migration of radionuclides to the biosphere.

The conceptual design consists of surface and underground facilities, connected by vertical shafts. The underground facilities are networks of tunnels. Two options are considered: a single level GDF at a depth of about 500 m in a Paleogene Clay formation with a thickness of about 100 m, and a multi-level GDF with HLW being disposed of at 500 m depth and LILW disposed of at a smaller depth. Several Paleogene clay formations exist at different depths across the Netherlands, potentially allowing a multi-level design. A thickness of clay of as little as 20 m has been demonstrated to be sufficient for the construction of disposal tunnels.







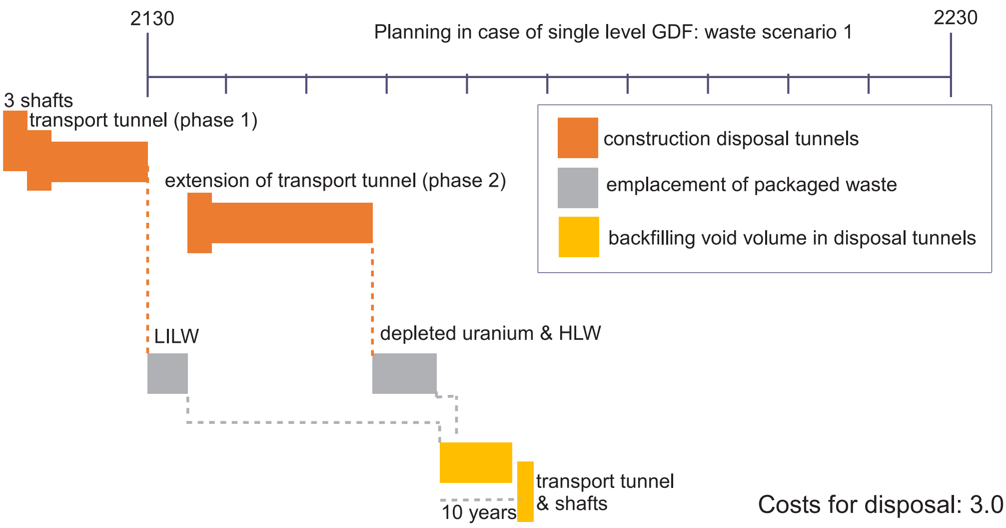
The GDF contains three groups of disposal tunnels: for HLW (vitrified high-level waste (vHLW), spent fuel from research reactors (SRRF), and non-heat-generating HLW) and for

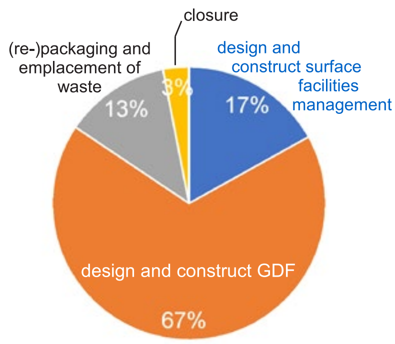
LILW and depleted uranium. Non-heat generating HLW is encapsulated in concrete containers. All heat generating HLW (vHLW and SRRF) is encapsulated in a supercontainer, adapted from the Belgian concept, consisting of a carbon steel overpack and a concrete buffer. A supercontainer for a single canister of vHLW is illustrated above.

A distinguishing feature of the disposal concept is the large amount of cementitious materials in the disposal tunnels and the waste containers. The disposal package for HLW includes a thick concrete buffer, the tunnels have a thick concrete liner, and a porous cementitious backfill is used to fill the gaps between the disposal package and the tunnel walls.

What are the costs?

The GDF design and the proposed implementation process allow an estimate to be made of the future costs that will be incurred. These estimates determine the financial contributions that are being paid by current waste generators in order to ensure that COVRA’s provision will be sufficient for GDF implementation. The total costs for disposal in 2130, based on the timetable shown below, are estimated to be 3 billion EUR(2022), 70% of this being for



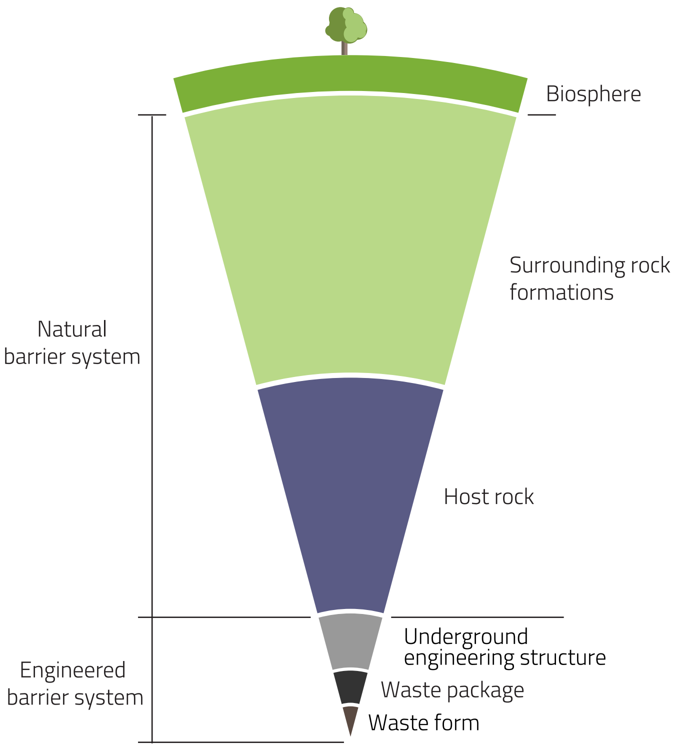


Costs for disposal: 3.0 billion euro (price level 2022)

design and construction. The cost estimate assumes that a definitive decision on the disposal method is made around 2100. There are several activities before waste packages can be emplaced at disposal depth such as the construction of the GDF that is composed of shafts and a structure of tunnels.
The construction of tunnels in the clay host rock can be done in several periods The first constructional phase is preceded with a site selection process. An underground observation phase of ten years is included. If this phase is extended to 50, or even 100 years, costs will not change significantly. The development of the disposal concept and costs for licensing are not included in the cost estimate. The planning scheme shows only activities related to the construction, operation and closure of the GDF.

The multibarrier system

The basis of geological disposal, which has been firmly established internationally for the last 45 years, is the concept of the multibarrier system, in which a series of engineered and natural barriers act in concert to isolate the waste and contain the radionuclides in the waste.



The relative contributions to safety of the various barriers at different times after closure of a disposal facility and the ways that they interact with each other depend upon the design of the disposal system. The design itself is dependent on the geological environment in which the facility is constructed. Consequently, the multibarrier system can function in different ways at different times in different disposal concepts.

Analysing safety

Quantitative analysis of the safety of the GDF is the central theme of a Safety Case. Estimates of potential radiological impacts to people are made for various future scenarios describing how the multibarrier system might evolve. The Normal Evolution Scenario (NES) is the central case considered and assumes undisturbed construction, operation and closure of the GDF, with no significant external disturbances of the multibarrier system in the future.
The OPERA safety assessment already recognised that, within the next 100,000 years to 1 million years, major climate change is to be expected, leading to periods of global cooling, lowering of sea level and the formation of permafrost and mid-latitude ice sheets, which might cover the GDF area. In COPERA, it is emphasized that this potential cover by ice sheets would be predominantly in the Northern part of the Netherlands, so that the safety assessments will be region specific. OPERA also identified a range of 'Alternative Evolution' scenarios for future assessment, as well as a range of speculative 'what-if' scenarios that might also be considered.
Human intrusion scenarios have been added in this COPERA Safety Case. To date, results have been calculated only for the NES.

What is the Natural Barrier System?

The host rock for the GDF, a Paleogene Clay formation, along with the overlying and underlying geological formations, comprise the natural barriers within the multibarrier system.

Paleogene clays

The Paleogene Clay host rock is the principal natural barrier and the most important barrier in the complete multibarrier system.
The clay contributes to post-closure safety by providing a low permeability barrier that provides long-term containment of radionuclides by ensuring that their transport away from the EBS can only occur by the extremely slow process of diffusion through stagnant porewaters. Paleogene clays are old and stable.
The Paleogene marine clays were sedimented on the seafloor over the period from c.23 million to c.66 million years ago. All Paleogene clays have the capability to contain the waste for at least one million years. Across the Netherlands, the top of the Paleogene sediments is usually deeper than 250 m, with a thickness of more than 200 m in most areas, implying a wide potential choice of useable clay host formations. For OPERA, a generic case for Boom Clay was selected, with the GDF at 500 m depth in a clay layer 100 m thick.

Paleogene clays are poorly indurated and are considered aquitards in groundwater management terms, due to their low permeabilities. The porewaters within these clays are virtually stagnant (i.e. there is no water movement) and diffusion can be assumed to be the dominant process by which chemical species can move through them. The clays are sufficiently plastic that they do not contain open fractures that could act as pathways for water (and radionuclide) movement. All clays display a strong retention or retardation capacity for many radionuclides.

It is recognised that there are current uncertainties related to the properties of the Paleogene clays and that these need to be studied in the future. For example, permeability measurements of these clays at relevant disposal depth have not yet been made in the Netherlands; validation of the retardation of radionuclides in these clays has started in COPERA but more experimental research is necessary for a more reliable quantification; the potential impact on radionuclide transport of gases produced by corrosion of GDF materials needs further study.

Overlying and underlying rock formations

The thick sequence of older Paleogene (c.66 to 23 million years old) and more recent Neogene (c. 23 to c.2.6 million years old) sediments is called the North Sea Group; it broadly forms the upper hundreds of metres of the landmass across the Netherlands. The rock formations that overlie the clay host rock contribute to the post-closure safety by isolation of the waste and protection of the Engineered Barrier System (EBS) and clay host rock from dynamic natural processes. The sedimentary formations that immediately underlie and overlie the Paleogene clays are sandy and permeable. These sandy formations contribute to post-closure safety because any radionuclides that diffuse out of the Paleogene clays and move through the large bodies of groundwater they contain will be dispersed and diluted, thus reducing their concentrations and their consequent hazard potential. Most Paleogene clays are surrounded by saline sandy formations that are too saline for groundwater extraction; aquifers are usually present in Neogene or Quaternary (c.2.6 million years ago to the present) sediments.

How might climate change impact the natural barriers?

During the Quaternary glacial cycles, the Netherlands has periodically been covered by ice sheets extending down across the Baltic and North Sea areas from a Scandinavian ice cap. Not every glaciation has been sufficiently intense to cause ice cover as far south as the Netherlands and, even in the more intense glacial periods, not all of the present country has been covered by ice.

Especially in the northern part of the Netherlands, ice-sheet loading can affect hydraulic conditions in the Paleogene clays at depth and potentially result in water movement in the clay. These region-specific studies have not been modelled since the CORA programme. The modelled ice-sheet thickness in CORA was 1000 m, which is now considered unrealistically large, based on OPERA research. Outward advective flow from the clay formation during compaction by ice sheet loading is thus expected to be smaller than was calculated in the CORA programme.

A concern in siting the Dutch GDF will be to avoid the possibility of deep erosion by glacial meltwaters after a future intense glaciation, during the change in climate from a glacial to an interglacial state. This is considered to be the only potentially detrimental geological process that could substantially affect the normal evolution of the multibarrier system. In a future GDF siting programme, it will be essential to look in more detail at the likelihood and consequences of such a scenario. Current understanding is that the current interglacial conditions are likely to persist for at least the next 100,000 years. If a further glacial period, followed by deglaciation and potential deep erosion, does not affect a GDF until some time after 100,000 years, the radioactivity of the HLW will already have been markedly reduced.

The OPERA safety assessment made the simplifying assumption of a constant interglacial climate for the next million years, and radionuclide transport was calculated assuming present climate conditions. For at least the next 100,000 years, this is considered reasonably realistic and also generally conservative, in that relatively warm conditions are characterised by higher flow in the overlying formations than during colder periods. Inclusion of glacial climates will be dealt with in future scenario analysis work.

What is the Engineered Barrier System?

The EBS, which provides both physical and chemical containment of the radionuclides in the wastes, is protected by the stable Paleogene clay formation which limits movement of groundwater to the EBS. Some decades after closure, the EBS will essentially be comprised of a heterogeneous, concrete-dominated system with interconnected porosity filled with stagnant waters in which chemical reactions are mediated by the slow diffusion of chemical species.

Cementitious materials comprise much of the EBS

Cementitious materials (tunnel liner segments, backfill, buffer, waste conditioning matrices) dominate by volume in each section of the GDF - up to 98% in the case of the tunnels containing vHLW waste packages. In OPERA, these materials were conservatively assumed to have no physical containment role after closure of the GDF, but in reality they fulfil an important safety function, by controlling the movement of water, by creating highly alkaline conditions in porewaters and by providing mineral surfaces that can interact with radionuclides in solution. During COPERA, several cementitious backfill materials and COVRA waste conditioning matrices have been investigated. Analysis of new experimental results confirm that the permeabilities of these types of concrete are lower than those of Boom Clay measured at 225 m depth. The lack in observed chemical or mechanical changes for small concrete specimens that were exposed to synthetic clay pore water or air for several years is a result of these low permeabilities, since ingress of little or no gaseous and dissolved species can take place. The enhanced understanding of the mechanisms of leaching allows a proper choice of the type of cement to be used to manufacture concrete, so that degradation of the mechanical strength can be prevented over the period of concern in the safety assessment. The cementitious materials can also provide an important chemical buffer that enhances chemical containment of many radionuclides by reducing their solubilities and promoting ion exchange. In particular, the type of ion exchange (cation or anion) is known to be pH dependent, which means that taking into account this favourable property requires knowledge of the evolution of the pH of concrete at different positions in the EBS.

The tunnel liner provides mechanical support for the tunnels during the operational phase. After closure, this support function is no longer assumed to function and overburden stresses can be transferred from the surrounding geological formations through the liner onto the mass of the EBS materials in the tunnels. The foamed concrete tunnel backfill is a porous backfill which can accommodate gas and reduce the gas pressure but in which microbial activity is feasible and may enhance the corrosion of metals. For this reason, the outer stainless steel envelope surrounding the concrete buffer of the waste package for HLW in earlier EBS designs is not included in the current EBS.

How will the waste packages behave in the multibarrier system?

Conservatively, only HLW waste packages have been assigned a post-closure containment role. The carbon steel overpack prevents water accessing the inner waste canister for a period determined by the ability of the concrete buffer to provide the chemical conditions to minimize steel corrosion. This prevents access of porewaters to the waste for as long as the overpack can sustain mechanical and early thermal stresses and resist failure through corrosion. It is designed to provide complete containment for thousands of years, beyond the early 'thermal period' of 1200 years when temperatures in the EBS are significantly elevated due to heat emission from the vHLW. Thermal calculations of the current design show that the heat emissions of SRRF are too low to significantly heat the clay host rock.

In the normal evolution scenario (NES), corrosion will eventually result in loss of integrity of the overpack safety function; this takes place at the so-called 'failure time' used in the safety assessment. Four cases for the lifetime of the overpack were studied in OPERA: 1,000 years, 35,000 years (the base case value), 70,000 years and 700,000 years. In COPERA, these calculations have been repeated when calculating releases of the long-lived radionuclide selenium-79, since this radionuclide was calculated to contribute most to the radiation dose rate in OPERA. Additional calculations were performed while taking into account only the low permeability of the backfill but, conservatively, not the permeability of the concrete buffer which is much lower. Mechanical analysis in COPERA shows that the thickness of the carbon steel overpack was sufficiently optimised in OPERA, so that no changes are proposed.

The Konrad Type II containers used for depleted uranium are assumed to have a failure time of 1,500 years. The 200 and 1,000 litre steel and cement LILW packages will contribute to chemical containment, but the conservative assumption in OPERA is that radionuclides are released instantaneously into the EBS porewaters after closure of the GDF, so an effective zero 'failure time' for LILW packages is used in the safety assessment.

Waste materials and gas production

The long-term behaviour of the solid waste forms, in particular how they react with and dissolve in pore waters in the EBS, influences the delay and attenuation of releases of radioactivity by limiting and spreading in time the release of radionuclides. The chemical reactions involved always consume water. Hydrogen gas can be produced by the corrosion of the metallic containers and from the waste forms, if they include metals. If the gas generation rate is larger than the capacity for migration out of the system as a dissolved gas, a free gas phase will be formed. This might result in gas-driven movement of radionuclides present in pore waters.

During COPERA, calculations have been carried out on rates of gas generation and its potential behaviour. These calculations show that the hydrogen evolved from the EBS in the case of vHLW does not exceed the hydrogen solubility in the porewater of the clay host rock. The hydrogen solubility would be exceeded for corrosion of aluminium in SRRF, assuming the hydrogen generation rates of solid pieces of aluminium exposed to aqueous solutions to be representative for the aluminium in SRRF surrounded by the low permeable concrete and clay.

In OPERA, the vHLW glass was conservatively assumed to dissolve either very rapidly, within 260 years, or else (still conservatively) over 20,000 years. These high glass dissolution rates were obtained from alteration rates of glass in which solid pieces of non-radioactive vitrified waste are exposed to a relatively large volume of an aqueous solution. During COPERA, more experimental results, in which the solid to liquid ratio is higher, have become available. Lower glass alteration rates are measured with these higher ratios. The calculated water consumption rates show that only the experiment with the highest ratio is representative for the vitrified waste form encapsulated in the concrete buffer. Also, the silicon concentration in equilibrium with the evolved cementitious minerals increases with reducing pH, further reducing the alteration rate of glass.

The radionuclide release rate from the waste form was assumed to depend on an alteration rate only for vHLW; for other wastes instant radionuclide release rate was assumed, after the so-called supercontainer 'failure time'. For LILW, an instant release rate was conservatively assumed to occur immediately upon closure of the GDF, except for depleted uranium. Depleted uranium, generated by URENCO during the uranium enrichment process, is the largest waste family by volume. Depleted uranium is also encapsulated in carbon steel, but with a smaller thickness than HLW. The uranium release rate into the clay host rock is constrained by an assumed uranium solubility. The assumed solubility is orders of magnitude larger than the measured concentrations of uranium in the clay pore water of Boom Clay.

How will the multibarrier system evolve over time?

The information available to quantify the performance of the multibarrier system is subject to different types and levels of uncertainty. OPERA allowed for this by making conservative simplifications, assuming poor performance, using pessimistic parameter values and omitting potentially beneficial processes. The results of the OPERA safety assessment are thus pessimistic forecasts of the performance of the multibarrier system. However, it is also essential for system engineering optimisation purposes to make best estimates of how we expect the multibarrier system to behave, acknowledging uncertainties along the way. This allows a balanced view that will inform later decisions on GDF design optimisation and, eventually, on acceptable site characteristics. This best estimate approach avoids over-engineering system components, allows waste to be disposed of according to their hazard potential, and prevents rejecting otherwise acceptable GDF sites.

OPERA presented a comparison (in different time frames) of the best estimate of the expected behaviour of components in the multibarrier system, based on the simplified assumptions of the safety assessment. This comparison is also done in COPERA. The expected behaviour is summarized below.

From closure to 1,000 years

The clay host rock is completely saturated at the start of the post-closure phase. The pores in concrete are partly filled with water and partly with the gases present in ordinary air: nitrogen, oxygen and traces of carbon dioxide. Clay pore water initially enters the backfill mainly through the joints between the concrete segments of the tunnel liner. The surface area of backfill exposed to water increases as the concrete in the tunnel segments become further saturated. Oxygen and carbon dioxide are consumed by reactions with minerals present in the cementitious phase of concrete, and nitrogen dissolves further as the saturation degree of concrete increases. The rate of corrosion of the carbon steel overpack is controlled by the amount of available water, the diffusion rate of dissolved iron away from the overpack surface, and the reducing (Eh) and alkaline conditions (pH) in the concrete buffer in the vicinity of the overpack. The small hydrogen generation rate during the anaerobic corrosion of the steel overpack ensures that only dissolved hydrogen can enter the clay host rock.

Up to 1,200 years, the temperature of the clay host rock in the vicinity of the EBS will be higher than its natural temperature at GDF depth, due to heat emission by the vHLW. There will be a thermal gradient from the HLW through the buffer, backfill and liner that will counteract inward flow of water from the clay host rock.

The lithostatic load of the geological formations overlying the tunnels has been taken up only by the tunnel liner in the operational phase. In the post-closure phase, there can be some additional support from the backfill and other EBS materials. The dissolved species in clay pore water entering the backfill and tunnel segments, and react with cementitious minerals leading to decalcification of these minerals, forming calcite, siliceous hydrates, some magnesium hydrates and magnesium siliceous hydrates. Leaching, which increases the porosity of concrete , has been minimized with a proper choice of the type of cement used to manufacture the concrete materials. An increase in porosity leads to a reduction in compressive strength. The porosity of concrete may however decrease by the formation of calcite. If a reduction in compressive strength is caused by decalcification of cement minerals, this reduction is localised to a few tens of mm at the edges of the concrete segments.

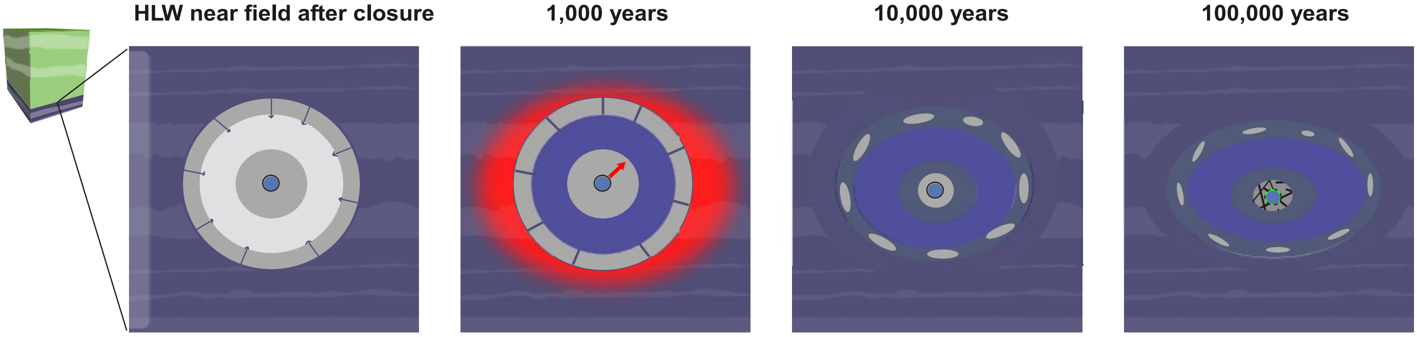
At the end of the thermal period, it is expected that the properties and geometry of the tunnels and other EBS materials will have changed very little, there will be limited chemical interaction between concrete and clay, and the carbon steel overpack will be mechanically and physically intact, corroding at a very low rate. The initial high radiotoxicity of vHLW and SRRF will have reduced considerably during this period of total containment.

Elsewhere in the GDF, anaerobic corrosion rates of the steel on the outer surfaces of the LILW waste packages are controlled by the availability of water, the diffusion rate of dissolved iron and the reducing and alkaline conditions, but also by the microbial activity of the backfill in the vicinity of these outer surfaces. The porous cementitious backfill allows dispersion of gas so that the formation of a free gas phase is minimized. The degree of saturation of the waste package concrete increases so that the alteration rates of the waste forms become larger than the rates under dry storage conditions. Dissolved radionuclides slowly diffuse through waste package concrete and other engineered barriers and can enter the clay host rock.

A **simplified** behaviour is modelled in the OPERA safety assessment. In the base case, nothing happens for HLW since all the carbon steel overpacks fail by complete corrosion, exactly at 35,000 years. For depleted uranium also nothing happens since the Konrad containers fail at 1,500 years. Other LILW containers 'fail' at time of closure of the GDF and all radionuclides are assumed to dissolve instantaneously in the EBS and are free to enter the clay host rock.

From 1,000 to 10,000 years

All pores in concrete barrier materials are almost completely saturated, a steady state of water consumption rate by the



The disposal tunnel has a concrete liner for mechanical support. After emplacement of the waste package in the tunnels, the void space between the package and the liner is backfilled with foamed concrete. Cementitious materials dominate the overall volume of the materials in the EBS. The low permeability of the concrete liner prevented drying of the clay host rock in the operational phase so that excavation-induced fractures are closed. Initially in the post-closure phase, clay pore water can access the backfill through the joints between the concrete segments in the liner. Later, the saturation degree of the concrete segments increases so that a larger surface area of the backfill is wetted by the clay pore water migrating through the liner.

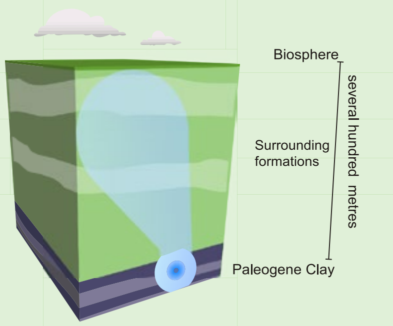
The waste heats the clay host rock in the vicinity of the EBS. Reactions between cement minerals and dissolved species from clay pore water have altered some of the backfill and liner concrete. This clay affected concrete has lost its strength and deforms under the load of the overburden. The slow anoxic corrosion rate ensures that the carbon steel overpack has not been breached.

The waste has cooled down and no longer heats the clay host rock. Reactions between cement minerals and dissolved species in the incoming clay pore water have led to a reduction in pH in the vicinity of the overpack. The anoxic corrosion rate of the overpack has increased. The vitrified waste form has not come into contact with water.

The radiotoxicity of the waste is lower than that of the original uranium ore. Fracture of the overpack allows contact between pore water and the vitrified waste. The majority of this waste becomes covered by a passivating film of hydrated glass and iron-phyllosilicates have been formed in the vicinity of the corroded steel.

1,000,000 years

Immobile, long-lived radionuclides will remain within the degraded EBS. Most other nuclides migrate very slowly through diffusion and retardation processes in the clay and eventually decay. Due to sorption, dispersion and dilution only extremely small concentrations of non-sorbing, long-lived nuclides reach the biosphere.



anaerobic corrosion process of the carbon steel overpack has been achieved. Dissolved iron and hydrogen diffuse further into the concrete buffer. The small connecting pore throat restricts diffusion of dissolved iron so that cementitious minerals start to react with dissolved iron, forming iron-affected concrete, a transformed medium. The mechanical strength of this medium is small so that the thickness of concrete buffer with a high strength, reduces. The highly alkaline conditions of the concrete buffer persist, so that the generation rate of the transformed medium is controlled by precipitation and not by ion exchange of dissolved iron with calcium.

Ingress of dissolved species in concrete pore water (bicarbonate, magnesium, sulphate) have further decalcified the cementitious minerals. If this decalcification leads to a decrease in compressive strength, the circular shape of the EBS starts to change slowly into an oval shape by creep of concrete and anisotropy of mechanical loads in the clay host rock.

By 10,000 years, vitrified HLW has almost achieved the same radiotoxicity as the uranium ore from which the fuel was originally manufactured. SRRF is more radiotoxic than uranium ore, due to the presence in the spent fuel of plutonium, which decays at a lower rate than the fission products and americium in vitrified HLW. During the production of vHLW, uranium and plutonium are removed from the waste and re-used to make fuel again. The content of uranium and plutonium in vHLW is therefore negligible compared to SRRF.

A **simplified, conservative** behaviour was modelled in the OPERA safety assessment. In the base case, there is no contact between and HLW and pore water since the carbon steel overpack is not breached. For depleted uranium, the steel containers fail by a combination of corrosion and lithostatic load, at an assumed time of 1,500 years. The reason for a earlier failure time of 1,500 years, compared to the 35,000 years for HLW overpack, is that the thickness of steel in the HLW overpack is larger than in the Konrad containers. The release of uranium into the clay host rock is limited by the solubility of uranium.

From 10,000 to100,000 years

The movement of dissolved species from the concrete materials into the clay host rock is very limited, since the concentration of dissolved calcium in the saline clay pore water is higher than, or similar to, the concentration in concrete pore water so that there is little concentration gradient to drive diffusion. The clay host rock itself will be little different from its original state. The continued ingress of dissolved species (e.g., magnesium, bicarbonate) from the clay host rock into the concrete materials further decalcifies these materials. The liner, backfill and buffer begin to lose their individual identity, to form a continuous mass of clay-affected concrete. Modelling studies show that the concrete buffer in the vicinity of the carbon steel overpack will retain its high pH.

It seems probable that the majority of the waste packages for heat-generating HLW would retain their containment function throughout this period. However, loss in compressive strength of the backfill and buffer, combined with reducing pH in the vicinity of the carbon steel overpack by further decalcification, and resulting in an increase of the corrosion rate of the overpack leading to an insufficient thickness with strength, may lead to breaching. At lower pH, cation exchange with cement minerals becomes dominant. The generation rate of the iron-affected concrete becomes controlled by ion exchange of dissolved iron, since ion exchange is a faster process than precipitation. The loss in compressive strength of concrete also increases the size of its connecting pore throats, so that diffusion values for dissolved iron become larger - perhaps larger than their values in the clay host rock. Both processes enhance a faster dissipation of dissolved iron in the vicinity of the carbon steel overpack, so that the corrosion rate increases. The corrosion rate can then become controlled by the permeability of the clay host rock instead of the (initial) lower permeability of the concrete materials.

After 20,000 years, the radiotoxicity of vitrified HLW has become lower than the radiotoxicity of the uranium ore from which the fuel was originally manufactured. The cross-over time for SRRF is towards the end of this period, at around 100,000 years.

The base case was **conservatively** modelled in the OPERA safety assessment by assuming that all waste packages for HLW fail at 35,000 years. At that time, there is contact between the waste and pore water, and the radionuclides becomes dissolved in the EBS. The high pH of the concrete buffer in the vicinity of the carbon steel overpack is conservatively modelled to remain for 80,000 years. Assuming a maximum anoxic corrosion rate in alkaline aqueous solutions of 2 μm per year to be representative, it takes 15,000 years to corrode 30 mm of steel. Assuming a maximum of 0.2 μm per year to be representative, it takes 150,000 years to corrode this thickness of steel. In COPERA, based on water consumption constraints, it has been calculated that the maximum possible corrosion rate is 1 μm per year for steel interfacing with the thick concrete buffer, using the updated design of the vHLW package and a permeability of concrete equal to COVRA's waste package concrete.

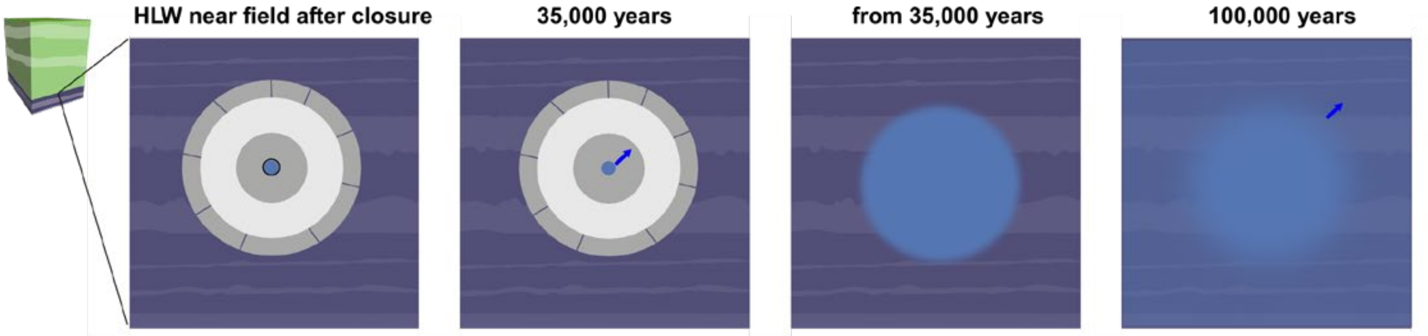
In OPERA, the vHLW is assumed to dissolve quite quickly in the base case: within 20,000 years. Modelling work in COPERA, based on water availability, estimates that this period would be much longer - at least 200,000 years. The release rate of dissolved radionuclides into the EBS is assumed to depend on the alteration rate of glass. For the SRRF, all the radionuclides are assumed to enter solution instantaneously. The approach developed during COPERA can also be used to estimate more realistically how radionuclides can be released into the EBS from SRRF as a function of the geometry of the multibarrier system and the low permeabilities of concrete and clay.

From 100,000 to one million years

At the start of the post-closure phase, there is some void volume within the vHLW stainless canister on top of the vitrified waste form. Because of this void volume, the overpack and the canister will crack as the thickness of the overpack decreases, its initially high strength reduces and the lithostatic load of the geological formations overlying the tunnels comes onto the supercontainer. This will be a progressive process over the 100,000 to one-million year time scale, with the formation of cracks staggered over many tens of thousands of years, so that access of pore waters to the vitrified waste form would be spread over long periods in time.

The initial alteration rates of glass are controlled by how fast pore water can enter the fractured canister. A passivation layer of hydrated glass is formed. In the vicinity of the corroding steel canister, the passivation capacity of this layer is not as strong as on a pure glass surface. The passivation layer is a mixture of clay minerals and zeolites. In the long-term, the properties of such a layer are similar to those of the rims found on basaltic glass (a natural volcanic glass). Estimated alteration rates of basaltic glass are about 0.1 μm per year. Uranium and plutonium from the degrading glass will be taken up by the clay minerals formed. Some radionuclides are not taken up by clay, for example selenium-79 with a half-life of 327,000 years. However, with the expected low alteration rates of glass, most of the selenium-79 is expected to decay within the vitrified waste form and not to be released to the surroundings. The small fraction of selenium-79 released diffuses slowly through clay-affected concrete, clay host rock and the surrounding rock formations. Dispersion and the large delay and dilution in space and time, implies that this mobile radionuclide can reach the biosphere only in very small concentrations.

After a million years, immobile and long-lived radionuclides will still remain within the clay-affected and iron-affected concrete of the EBS. Uranium-238, the main component of depleted uranium, will remain in the EBS until inexorable processes of geological erosion over hundreds of millions of years disperse it into new sediments and rocks. The residual uranium within the degraded EBS will behave like a naturally occurring ore body.



Up to the time of failure of the carbon steel overpack, which is assumed to take place after 35,000 years, the system remains effectively unchanged, with only slow corrosion of the overpack occuring. The failure time of the carbon steel overpack is determined by the corrosion rate and steel thickness.

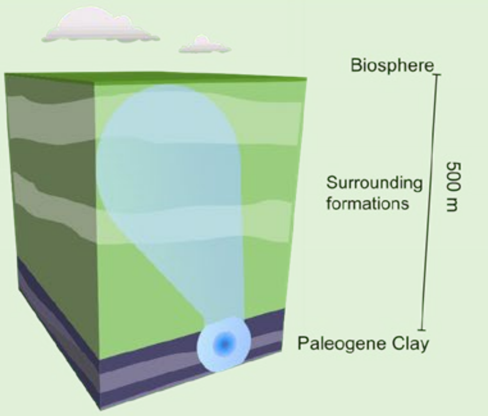
At this point, it is assumed that all the overpacks fail and the total glass surface area, including fractures in the vitrified waste form, becomes available for dissolution. The dissolution rate of radionuclides is determined by the cracking factor and the alteration rate of glass.

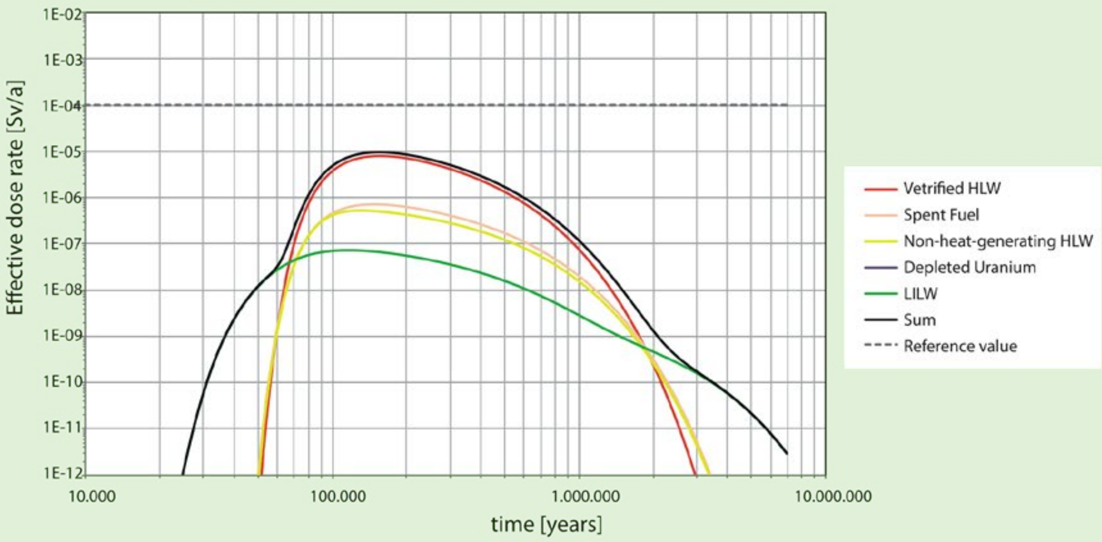
In the SA model used in OPERA, all the components in the disposal tunnels, including the waste packages and tunnel liner are modelled as a single homogeneous volume within which radionuclides are generated uniformly, at a rate determined by the dissolution rate of vitrified waste.

More and more radionuclides are released into the EBS due to gradual dissolution of the waste form. Mobile radionuclides are dispersed further into the clay host rock and then into the aquifer system, which can result in uptake in the biosphere.

100,000 - 1,000,000 years

The wastes that dominate the calculated exposures are vitrified HLW and SRRF, even though the volumes of these waste are relatively small compared to other wastes. The calculated peak exposure is about 10 μSv per year, at about 200,000 years into the future. This peak is ten times lower than the reference value of 0.1 mSv per year and about 150 times lower than average natural background radiation exposures.





The simplified geometry used in the safety assessments assumes that the full surface area of the vitrified waste form is in contact with pore water after the failure lifetime of the overpack. The illustration above summarises the simplified behaviour modelled in the OPERA safety assessment over each of the periods discussed above and can be compared with the previous illustrations of expected behaviour. Dissolved radionuclides from the EBS enter directly the clay host rock. The containment function of the clay host rock is for non-sorbing chemical elements such as selenium limited to its small permeability and reducing conditions. People are eventually exposed to releases, the highest contribution to the dose rate was calculated to be from selenium-79 released from the vitrified HLW. In COPERA, there is the waste form releasing radionuclides to concrete materials. All concrete materials have been assumed conservatively to have the same permeability as the porous cementitious backfill. If the permeability of the backfill is taken into account, the calculated contribution of the dose rate from vitrified HLW decreases by more than an order of magnitude. The second largest contribution comes from iodine-129 in spent fuel (SRRF), since this is also a mobile long-lived radionuclide. The contributions from non-heat generating HLW and LILW come from radionuclides that are cations, which were assumed in OPERA not to be retarded by the clay host rock. However, analysis of experimental measurements from clay host rocks, as well as available literature, shows that some retardation of these cations is likely. In the base case, despite the assumed high solubilities of uranium, the contribution to the dose rate from depleted uranium is negligible and therefore not visible at the scale used in the release calculations. This negligible contribution to the dose rate from depleted uranium is judged to be realistic.

How safe is the multibarrier system?

The safety assessment calculates the potential radiological impacts of the multibarrier system on the environment over the timescales discussed. The results are compared with indicators and reference values used for judging acceptable levels of safety. The assessment model splits the geological disposal system into compartments, evaluates radionuclide behaviour within each and calculates transfers between them.

The biosphere acts as the receptor for any radioactivity that moves upwards from the geosphere. Reference biospheres developed by the IAEA are used to determine how people might be exposed to radionuclides from the multibarrier system. A uniform temperate climate is assumed for the whole period of the OPERA calculations. This is considered adequate for the present preliminary safety assessment in this phase of the Dutch geological disposal programme.

The radiological impacts (radiation exposure or dose) of ingestion, inhalation and external radiation by radionuclides entering a well, surface water bodies (rivers, lakes, ponds) and wetlands is included in the reference biospheres. The modelled well is small, at shallow depth and supplies a family with all its drinking and other water, including water used for crop irrigation and livestock.

The calculated potential radiation dose to an individual is compared with a reference dose. In Dutch legislation, no dose constraints are yet defined for geological disposal, so the reference value has been set at 0.1 mSv per year, a value used in most other national programmes. The flux of radiotoxicity from the multibarrier system into the biosphere is another useful reference value; it can be compared to the flux from radionuclides naturally present in the overburden.

The bulk of the calculated total radiotoxicity in the system remains in the EBS and the clay host rock. About a tenth of the total radio-toxicity results from the depleted uranium, which remains within the EBS, where its low solubility and mobility continue to contain it. Only a tiny fraction of the radiotoxicity enters the overlying geological formations; by the time of peak releases to the biosphere at 200,000 years, this fraction represents only about one millionth of the activity that is contained within the multibarrier system. As expected in this disposal concept, the low permeability clay host rock and concrete in the multibarrier system represent the most effective barriers. In summary, within a few hundred thousand to a million years, almost all the radioactivity initially in the GDF has either decayed within the EBS or the clay host rock, only a tiny fraction has migrated out to be diluted and dispersed in the overlying formations and biosphere, and the multibarrier system has effectively performed its isolation and containment task.

The exception to this picture is depleted uranium. This comprises more than half the mass of the waste materials in the GDF but contains only about 0.2% of the total radioactivity at the time of disposal. However, its principal radionuclide (naturally occurring U-238) has a half-life of 4.5 billion years, which means that it does not decay perceptibly within tens of millions of years. In calculations run out to the very far future, uranium series radionuclides are the only significant contributors to exposures, but in the Normal Evolution Scenario (NES) these exposures occur only after some tens of million years into the future. A further key observation is that it is not possible to mitigate these exposures by any realistic optimisation of disposal system engineering. However, they are a minute fraction of natural background radiation doses and arise from what is effectively a natural material that, owing to its low mobility, is expected to remain within the geological environment. Investigations of the natural uranium already contained in the Paleogene clays are expected to elucidate the key processes for uranium migration and derive representative parameter values for the post-closure safety assessment.

Overall, even using pessimistic approaches, the performance assessment calculations for the NES show that potential radiation exposures to people in the future are orders of magnitude below those currently experienced by people in the Netherlands due to natural sources of radioactivity. Also, they would not occur until many tens or hundreds of thousands of years into the future. The calculated impacts for the NES are also well below typical, internationally accepted, radiation protection constraints for members of the public.

The NES represents the most likely evolution of the disposal system and remains the focus for calculations in the future, with other scenarios that address climate changes to be included in future post-closure safety assessments. Alternative evolution scenarios are less likely but need to be assessed, because they illustrate the redundancies in the multibarrier system, also in extreme climate states. What-if scenarios are not likely but contribute to the testing of individual barriers in the multibarrier system. Human intrusion scenarios have so far only studied radiological exposure to people working at drilling sites and not any public exposures. To minimise the probability of public exposures by human intrusion, COPERA made the choice to focus on saline Paleogene clays overlain and underlain by saline Paleogene sandy formations where there is little incentive for extraction of groundwater.

Can the GDF be optimised for post-closure safety?

Optimising the radiological protection provided by the multibarrier is an important objective for the future. In OPERA, all types of waste were proposed to be disposed of at the same disposal depth, but, as explained earlier, a multilevel design of the GDF has been developed. This depth segregation means that long-term interactions between degradation products of the different types of waste are less likely, and the sandy formations between the clay formations also enhance dissipation of degradation products such as gases.

The multilevel GDF also reduces the footprint occupied by the waste, so that the likelihood of human intrusion is further reduced. In any case, extraction of core samples of EBS and waste materials would lead any competent company or organisation to cease drilling, at least temporarily, and report to the relevant authority.

Conclusions

What is the feasibility of constructing the GDF?

The disposal concept is based on the well-developed Belgian GDF design for Boom Clay, but its construction in the Netherlands could utilise other available Paleogene formations with suitable properties over a wide depth range. While there is certainly flexibility in choosing an appropriate host formation (or formations), the detailed knowledge of the geotechnical properties of Dutch Paleogene clays at relevant disposal depths that we need to refine our designs and safety assessments is currently poor. During COPERA, good quality Paleogene clay cores have been obtained at 400 m. These cores are currently being investigated in SECUUR, a research project led by Delft University of Technology. More needs to be known about the nature and variability of Paleogene Clay properties and about the in-situ stress regime on a regional basis across the Netherlands in order to refine the current GDF layout concept, in which one transport tunnel intersects all the disposal tunnels at the same disposal depth. Existing tunnelling techniques using a tunnel-boring machine can be used to excavate the clay host rock.

The range in disposal depth for HLW considered is from 200 m to 1,000 m. The minimum disposal depth is sufficient for isolation of HLW. As the temperature of the clay host rock increases with depth, 1,000 m is currently expected to be a maximum, for an acceptable working temperature. Costs increase with increasing depth, predominantly due to the greater required thickness of concrete segments in the liner of disposal tunnels; this reduces the disposal volume so that the tunnel length needs to be larger. For mechanical stability, the spacing between the disposal tunnels also needs to be larger, requiring a larger transport tunnel. The disposal depth at which the costs of the GDF become prohibitive is yet to be calculated.

What is the feasibility of siting a GDF?

Siting studies are currently foreseen after 2050, but there is confidence today that suitable locations for a GDF in Paleogene clays with appropriate thickness and depth are available, but the data on their characteristics need to be improved. Significant uncertainties in depth-thickness distributions of Paleogene clays are present since most of the data originate from oil/gas exploration wells, where there has been little interest in characterising the clays.

A siting programme will need to avoid certain geological structures and features, and guidelines and criteria for doing this will need to be developed. Factors that will need to be taken into account include natural resources, variability of Paleogene clay properties, levels of seismic activity and evidence of past deep glacial erosion.

Future development of the concept will also depend on obtaining better data on regional hydrogeological and geomechanical properties of the formations overlying and underlying, the Paleogene clays. This will require access to boreholes and cores from relevant disposal depths. At the current programme phase, data from boreholes are required, not for commencement of a siting programme, but rather for achieving broader validation of some of the geoscientific assumptions.

Other potential GDF host rocks exist in the Netherlands, some of which have been evaluated in the past and all of which will be studied in more detail in the future. These include Zechstein rock salt, for which a COPERA Salt Safety Case has been developed, in parallel to this COPERA Clay Safety Case.

It is recognised by COVRA that siting a GDF involves considerably more than evaluating technical factors. Any future siting programme will need to take account of societal requirements and will be staged, progressive and consensual in nature.

Does the multibarrier system provide adequate safety?

The multibarrier system provides complete containment and isolation of the wastes during the first few hundreds to a few thousand years during which the hazard potential of the wastes is at its highest, but is decaying rapidly. Beyond 10,000 years, we expect that any residual radioactivity that escapes the degraded EBS will be contained by the clay host rock for hundreds of thousands to millions of years. A minute fraction of highly mobile radioactivity will move into surrounding geological formations on this timescale, but will be diluted and dispersed in deep porewaters and groundwaters, resulting in concentrations that cause no safety concerns and are well below natural levels of radioactivity in drinking water.

Other evidence underpinning safety

Natural and archaeological analogues of the preservation of materials in clays show that all degradation processes can be much slower than typically modelled. The preservation of ancient woods for millions of years in Neogene clays in Italy (see image next page) and Belgium is a good example of how the absence of groundwater flow and the presence of anoxic conditions contribute to very long-term preservation, even of fragile organic material. The 2,000 year preservation of Roman iron objects in similar anoxic conditions (see image next page) supports the assumptions on the minimum longevity of the carbon steel overpack of the waste package for heat-generating HLW. Roman cements and concretes show that the massively concrete-dominated engineered barrier system can maintain its physical properties and structural stability for thousands of years.

Natural radioactivity, present in all rocks, soils and waters around us, provides a useful yardstick against which to compare the impacts of any releases from the multibarrier system. The unavoidable natural radiation exposures to which we are all subject are higher than those from even our pessimistically calculated releases. We live in, and human-kind has evolved in, a naturally radioactive environment.

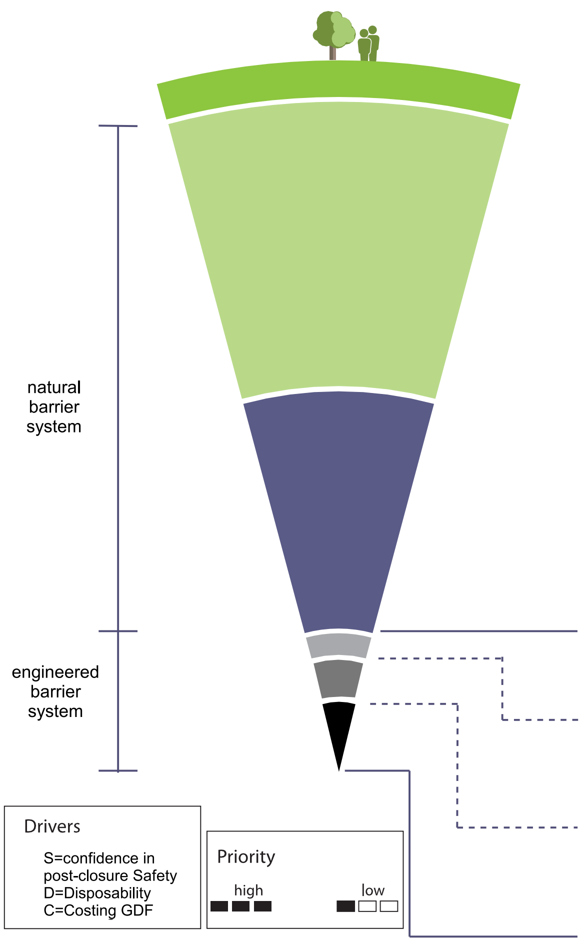
Confidence in the reliability of the OPERA safety assessment calculations is also enhanced by the fact that they are broadly similar to those estimated independently for a wide range of wastes and host rocks, in other national programmes.

Improving the design and Safety Case

A number of processes and scenarios that could affect or alter the NES have not yet been treated and thus constitute open issues that will require further R&D and safety assessment. The principal uncertainties that have been identified will be addressed by future studies. Not all of the work is required in the next decades; some will be staged over several iterations in COVRA's long-term research programme. A roadmap that starts with the identification of the key topics that need to be addressed in future work has been developed for this future RD&D. The illustration below shows these key topics for the main components in the disposal system, along with the drivers for carrying out further work and the priorities currently attached to each component. The highest priority is associated with obtaining further information on the Paleogene clays.

Awareness of the GDF design concept and its requirements in terms of depth, area and geological conditions will facilitate fitting this facility into national planning policies and priorities for the use of underground space. At present, there are good prospects for disposing Dutch radioactive waste within the Paleogene clays, but more data need to be collected on its properties and their variability at relevant depths.

The existence of COPERA and its findings are important contributions to satisfying the Netherlands' obligations under both EC Directive 2011/70/EURATOM and the IAEA Joint Convention, showing that substantial progress has been made on the national programme. The project also supports the Netherlands' position of carrying out a dual-track (national and potential multinational) policy for radioactive waste management. The results can be used as the Netherlands' contributions to the development of multinational projects.



Component	Key topics	Drivers	Priority
Biosphere	IAEA reference biospheres provide currently sufficient knowledge	S ■□□ D ■□□ C ■□□	4
Surrounding rock formations	Salinity in Paleogene sands Trace elements in Paleogene sands	S ■■■ D ■□□ C ■■□	2
	Salinity in deeper ground model Effect of climate change	S ■□□ D ■□□ C ■■□	3
Host rock: Paleogene clays	Geotechnical properties Diffusion dominated transport Ion exchange and solubility Quantification of thicknesses and depths	S ■■■ D ■■□ C ■■■	1
Underground engineering structure	Scale up to larger waste inventories Different disposal depths Backfill (sufficient knowledge)	S ■□□ D ■□□ C ■■■	2 4
Waste package design	Consumption, generation and transport of water HLW containment	S ■■□ D ■□□ C ■■□	2
Waste form	Long-term behaviour (water, gas) at disposal scale Depleted uranium as aggregates Not yet stored waste forms	S ■■□ D ■■□ C ■□□	2

Visiting address
Spanjeweg 1
havennummer 8601
4455 TW Nieuwdorp
Vlissingen-Oost

Postal address
Postbus 202
4380 AE Vlissingen

T 0113-616 666
F 0113-616 650
E info@covra.nl

This report presents an summary of the results and conclusions of the Safety Case for a geological disposal facility in the Paleogene Claysof the Netherlands.
The report is a scientific/technical document that describes engineering and geological requirements needed to assure that a safe GDF can be implemented in the Netherlands.

Rapportnummer: 25028