COVRA NV

SUMMARY

OPERA SAFETY CASE

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Summary

The principal objective of this report is to present an overview of the results and conclusions of the OPERA Safety Case for a geological disposal facility (GDF) in the Boom Clay, which will contain almost all radioactive wastes arising in the Netherlands. Because it marks a major milestone in the Dutch radioactive waste management programme, the report also covers other research performed in the framework of the wider OPERA research programme.

The OPERA programme and future work on geological disposal is being structured around the development of a series of Safety Cases for a GDF in the Netherlands. The national context of the geological disposal programme, the wider than usual range of objectives and the wide target readership, mean that there are significant differences between the Initial Safety Case presented here and recent national Safety Cases published in other countries. The OPERA Safety Case is less comprehensive, given that it is an initial analysis that will be followed by further iterations. This initial Safety Case covers only one of the options for geological disposal that are being studied in the Netherlands. The report focuses on clay as a host rock but the option of disposal in salt remains open and no siting decisions will be taken in the Netherlands for many decades into the future.

On the other hand, the report is wider in scope than many other national Safety Cases. To make the report accessible to a wide readership, explanatory material has been included to describe the basic concepts involved in geological disposal and to summarise the current international consensus on the recognised approaches to achieving safety and to structuring a technical Safety Case for a GDF. In addition, proposals for future scientific and technical studies have been developed, using the information gathered during preparation of the Safety Case. These are presented in a roadmap, laying out all COVRA's (Centrale Organisatie Voor Radioactief Afval) ongoing activities leading eventually to implementation of a GDF in the Netherlands.

The present report is a scientific/technical document. It describes engineering and geological requirements needed to assure that a safe GDF can be implemented in the Netherlands. The OPERA project team is, however, fully aware that a successful GDF programme must address both technical and societal issues. OPERA has initiated work on communication with the Dutch public, to which this report is a contribution. A separate, complementary synthesis report deals with the wider, societal issues of disposal, including stakeholder engagement and conditions for an inclusive process for long-term decision-making on disposal [Heuvel van den, 2017]. This report by the OPERA Advisory Group also provides recommendations on how this important issue will be continued in future projects.

What's new in OPERA?

Conservative estimates have been developed quantifying the levels of safety achievable for a GDF constructed in the Boom Clay and containing all of the waste streams produced in the country.

An updated design concept has been produced for the GDF – in particular with an engineered barrier concept including a supercontainer for the most active wastes.

Recent developments in other countries considering deep disposal in clays have been fully integrated: in particular, there has been close cooperation with the Belgian disposal programme.

The structure of the OPERA project focuses on development of an Initial Safety Case: this also gives a framework for future planning.

The inventory of waste types is comprehensive: in particular spent research reactor fuel is treated in detail and the focus on depleted uranium as a waste form is novel.

The use of publicly accessible data on a potential host rock in the Netherlands.

The cost estimate for a GDF in Boom Clay has been updated based on demonstrated construction and emplacement techniques from the Belgian programme.

Based on the results, priorities and specific goals have been developed for future work in the Netherlands, which are integrated in a long-term roadmap.

The execution of the research was coordinated by the national Waste Management Organisation, COVRA and carried out by a wide range of Dutch research entities, with significant input also from organisations in other countries.

Introduction

Nuclear technologies are used in electricity generation, medicine, industry, agriculture, research and education. These technologies generate radioactive wastes that must all 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 confinement is disposal in a stable geological environment beneath the Earth's surface, by emplacement in a 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, more than 100 years from now. The extended timescales allow flexibility in case options other than disposal in a national GDF become available, such as disposal of Dutch waste in a shared, multinational repository.

OPERA is not the first Dutch programme on geological disposal. It includes novel elements relative to its predecessor programmes, OPLA (1982-1992) and CORA (1995-2001).

The main thrust of the OPERA Safety Case report 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 overall OPERA programme 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, involving tasks covering many areas of expertise.

How much waste is destined for geological disposal?

The OPERA waste inventory is based on the Dutch base case nuclear scenario: no new nuclear power plants and operation of the present nuclear power plant until its intended closure in 2033. The expected eventual inventory of wastes from all sources that is destined for geological disposal is summarised below. These are relatively small quantities when compared with other nuclear power nations.

Waste Category	In storage (2130)		Packaged for disposal (2130)		
	Volume [m3]	Weight [tonne]	Number of containers	Volume [m3]	Max weight [tonne]
Processed LILW	45000	150000	152000	45000	150000
Depleted uranium	34000	110000	9060	40000	182000
Vitrified HLW	93	191	478	3388	9560
Spent research reactor fuel	104	99	75	638	1800
Other HLW	256	600	700	5104	14400

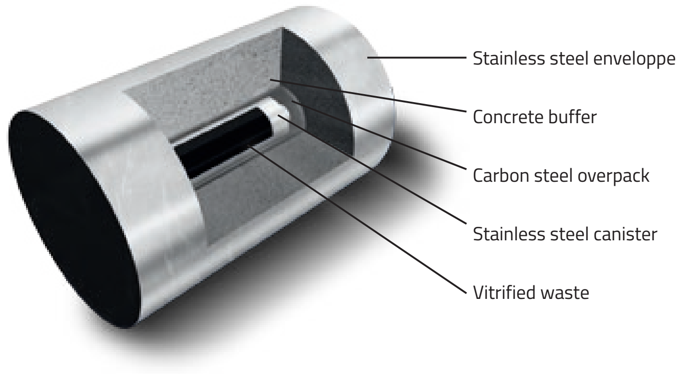
What could a Dutch a geological disposal facility look like?

The GDF design developed for OPERA is based on the universally adopted 'multibarrier system' of natural and engineered barriers that contain and isolate the wastes and prevent, reduce, or delay migration of radionuclides from them to the biosphere.

It consists of surface and underground facilities, connected by vertical shafts and (optionally) an inclined ramp. It is located at a depth of about 500 m in the Boom Clay formation. A thickness of about 100 metres of Boom Clay is considered sufficient both to facilitate excavation of the GDF and to provide an adequate barrier function, although smaller thicknesses might also be feasible.

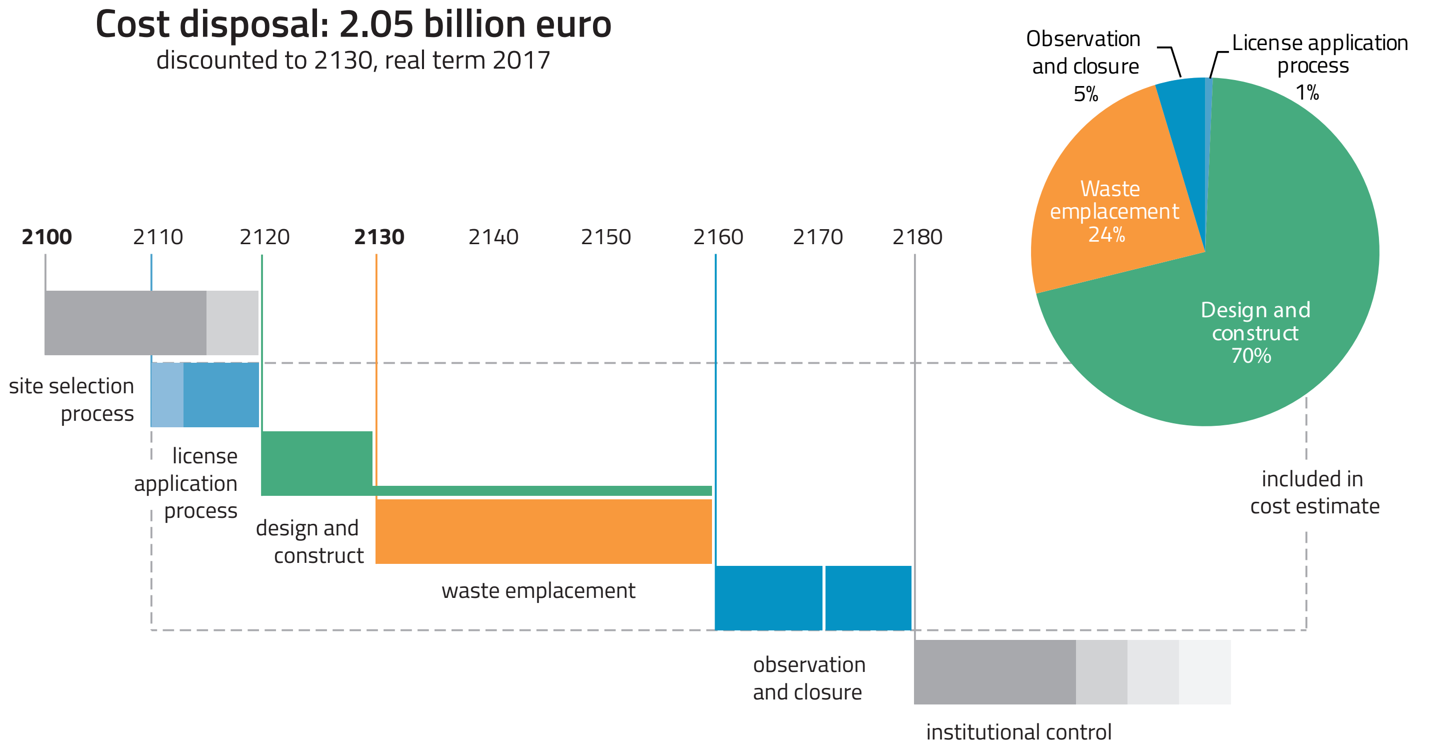
The GDF contains four groups of disposal tunnels with different dimensions: for vitrified high-level waste (vHLW), for spent fuel from research reactors (SRRF), for non-heat-generating high-level waste (HLW) and for the disposal of low and intermediate level waste (LILW) and depleted uranium. The most radioactive wastes are encapsulated in a **supercontainer,** adapted from the Belgian concept, consisting of a carbon steel overpack, a concrete buffer and stainless steel envelope, as illustrated below for one vHLW canister.

A distinguishing feature of the OPERA disposal concept is the amount of cementitious material in the disposal tunnels and the waste containers. The supercontainers use a thick cement buffer, the tunnels use a thick concrete liner and cement or concrete is used to fill the gaps within the supercontainers and between the supercontainers and the tunnel walls.



Analysing safety and costs

Quantitative analysis of the safety of the GDF is the central theme of this Safety Case. Estimates of potential radiological impacts to people are described for various future scenarios of how the disposal system might evolve. The Normal Evolution Scenario (NES) is the central case considered and assumes normally progressing, undisturbed construction, operation and closure of the GDF, with no significant external disturbance of the disposal system in the future. The OPERA safety assessment recognises 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. OPERA also identified a range of 'Altered Evolution' scenarios for future assessment, as well as a range of speculative 'what-if' scenarios that might also be considered.

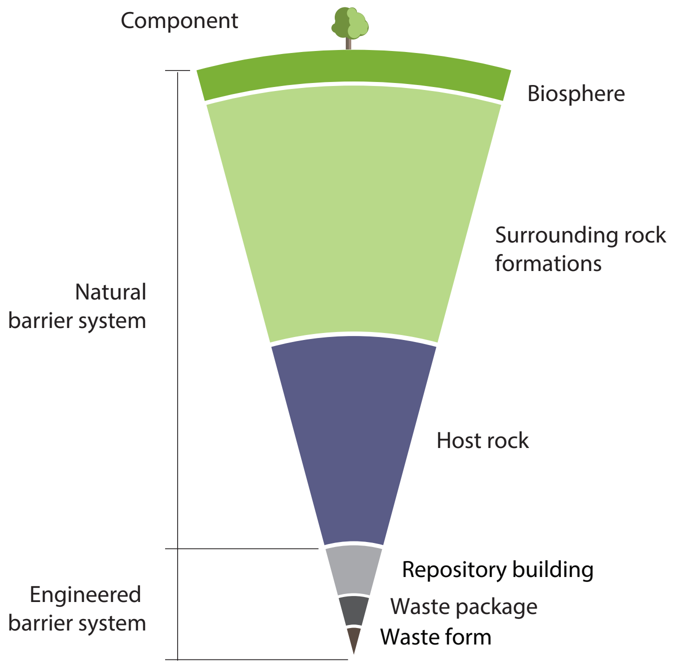


The GDF design and the proposed implementation process allow an estimate to be made of the future costs that will be incurred. These estimates determine the financial contributions that are being paid by current waste producers in order to ensure that the national waste fund will be sufficient for GDF implementation.

The total costs for disposal in 2130, based on the timetable shown at the left, are estimated to be EUR(2017) 2 billion, 70% of this being for design and construction. The cost estimate is based on a definitive decision on the disposal method being made around 2100. An underground observation phase of ten years is included, to facilitate retrieval of waste packages before closure if required. If this phase is extended to 50 or even 100 years, costs will not change significantly. The development of the disposal concept and the site selection process are not included in the cost estimate.

The multibarrier basis of the GDF

The basis of geological disposal has been firmly established internationally for the last 30 years on the concept of the multibarrier system, whereby a series of engineered and natural barriers act in concert to isolate the wastes and contain the radionuclides that they contain.



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.

What is the Natural Barrier System?

The host rock for the GDF, the Boom Clay formation, and the overlying geological formations comprise the natural barriers within the multibarrier system.

Boom Clay

The Boom Clay is the host rock for the GDF, the principal natural barrier, and the most important barrier in the complete multibarrier system. The Boom Clay's contribution to post-closure safety is to provide a stable, low permeability barrier that isolates and protects the wastes and the Engineered Barrier System (EBS) from dynamic natural processes and prevents water from flowing through them. It provides long-term containment of radionuclides by ensuring that their transport away from the GDF can only occur by the extremely slow process of diffusion in stagnant porewaters. The Boom Clay is old and stable. It was deposited during the Oligocene Epoch around 30 million years ago and has the capability to isolate the waste from people and environment for at least one million years. It is present in a potentially appropriate depth range of 300 to 600 m across large parts of the NW and SE Netherlands, in thicknesses of greater than 50 m. For OPERA, a generic case was selected with the GDF at 500 m in a clay layer 100 m thick.

The very low permeability of the Boom Clay means that its pore waters are effectively 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 it. It is sufficiently plastic that it does not contain open fractures that could act as pathways for water (and radionuclide) movement. The Boom Clay displays a strong retention or retardation capacity for many radionuclides.

It is recognised that there are uncertainties related to the properties of the Boom Clay that need to be studied in the future. For example, permeability values of Boom Clay measurements of relevant disposal depth have not yet been made; the retardation of radionuclides in Boom Clay needs to be quantified more reliably; the potential impact on radionuclide transport of gases produced by corrosion of GDF materials needs further study.

Overlying and underlying geological formations

The Boom Clay is part of a thick sequence of Paleogene and Neogene sediments called the North Sea Group, which broadly forms the upper hundreds of metres of the landmass across the Netherlands. The sedimentary formations that immediately underlie the Boom Clay and overlie it to the surface are weakly consolidated or unconsolidated mixed layers of variable thicknesses of sand, silt and clay. These are permeable and include aquifers. They contribute to post-closure safety because any radionuclides that diffuse out of the Boom Clay and move through these large bodies of groundwater will be dispersed and diluted, thus reducing their concentrations and their consequent hazard potential.

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.

Ice-sheet loading can affect hydraulic conditions in the Boom Clay at depth and potentially result in water movement in the clay. This was modelled in the previous research (CORA) programme, but OPERA has not yet taken this modelling further. The modelled ice-sheet thickness in CORA was 1000 metre, which is now considered unrealistically thick, based on OPERA research. Outward advective flow from the Boom Clay during compaction by ice sheet loading is thus expected to be smaller than calculated in the CORA programme.

A concern in siting the Dutch GDF will be to avoid the possibility for deep erosion 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 OPERA disposal 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 interglacial conditions are likely to persist for around 100,000 years. If 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 current OPERA safety assessment makes the simplifying assumption of a constant interglacial climate for a period of a million years and beyond, and radionuclide transport is 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 Boom Clay formation, with no movement of groundwater in the GDF. Some decades after closure, the whole EBS will essentially comprise stagnant waters in a heterogeneous barrier system with interconnected porosity, where chemical reactions are mediated by the slow diffusion of chemical species through the porewaters.

Cementitious materials comprise much of the EBS

Cementitious materials (tunnel liner, backfill, buffer, waste conditioning matrices) dominate the overall volume of materials in each section of the GDF – up to 98% in the case of the super-containers for vHLW. In the OPERA concept, they are assumed to have no physical containment role after closure of the GDF, but they fulfil an important safety function, by controlling the chemistry of the EBS, imposing highly alkaline conditions in porewaters and providing mineral surfaces that can interact with radionuclides in solution. In this way, the cementitious materials provide a substantial chemical buffer that favours chemical containment of many radionuclides by reducing their solubilities and promoting sorption. The chemical and mechanical evolution of the cementitious materials over time thus needs to be evaluated.

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 has a low permeability to water but relatively high gas permeability, which limits the build-up of gas in the disposal facility.

How will the waste containers behave in the GDF?

Conservatively, the only container assigned a post-closure containment role is the inner carbon steel overpack of the HLW/SF supercontainer. This prevents access of porewaters to the waste for as long as it can sustain mechanical and early thermal stresses and resist failure through corrosion. It is designed to provide complete containment for 1000 years, beyond the early 'thermal period' when temperatures in the EBS are significantly elevated due to heat emission from the vHLW and SRRF.

In the NES, corrosion will eventually result in loss of integrity of the overpack safety function, resulting in the so-called 'failure time' used in the safety assessment. Four cases for the longevity of the supercontainer overpack have been studied in OPERA: 1000 years, 35,000 years (the base case value), 70,000 years (the realistic corrosion case) and 700,000 years. The thickness of the overpack can be optimised to meet any specific longevity performance requirements that might arise from further consideration of the results of the current or future OPERA assessments.

The Konrad Type II containers used for depleted uranium are assumed to have a failure time of 1500 years. The 200 and 1000 litre steel and cement LILW packages contribute to chemical containment, but the OPERA conservative assumption 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 material behaviour 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, contributes to the delay and attenuation of releases of radioactivity by limiting and spreading in time the release of radionuclides.

The **vHLW** glass is conservatively assumed to dissolve either very rapidly, within 260 years, or (still conservatively) over 20,000 years, or at a more realistic and much slower rate, taking more than 6 million years to dissolve completely. Owing to its high corrosion rate, SRRF provides relatively little containment function to limit the rate of release of radionuclides once pore waters have penetrated the supercontainer overpack. Degradation behaviour is controlled by corrosion of the aluminium matrix and cladding, which will corrode rapidly, as aluminium is not thermodynamically stable in water. A pessimistic assumption is made of instant release of all radionuclides into EBS pore waters upon failure of the overpack.

Gas can be generated in the GDF by metal corrosion or microbial activity in several of the wastes and the materials of the EBS, with anaerobic corrosion of metals expected to be the main mechanism by which hydrogen gas can be formed. 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. Hydrogen from the corrosion of steel is calculated to remain in solution, but the higher generation rate from aluminium would lead to a gas phase being present. In this case, pathways could be created by dilation of the clay, temporarily creating cracks and a mechanism for fluid flow. Work in other national programmes suggests that the effects are largely or wholly reversible. Information available from the Belgian and other national programmes suggests that the rate of gas production in the GDF could be accommodated by dispersion in the geosphere, but this will be design and site specific.

OPERA has not yet carried out calculations to assess gas-mediated migration of radionuclides in pore waters, or the potential radiological impacts of gaseous species. This will ultimately depend on the specific properties of the host rock at the site eventually selected for the GDF and thus will be an issue to be addressed in detail nearer to that time. If it is thought that adverse impacts are possible, then an engineering solution might be considered.

The largest LILW family by volume is depleted uranium, generated by URENCO during the uranium enrichment process. The second largest waste family is compacted waste collected from some two hundred industrial and medical organisations. The third largest waste family arises from the production of medical isotopes. Although the cementitious materials used to grout the wastes provide both chemical and physical containment, the OPERA safety assessment assumes instantaneous release of radionuclides upon failure of the outer containers, which is conservatively assumed to occur immediately upon closure of the GDF.

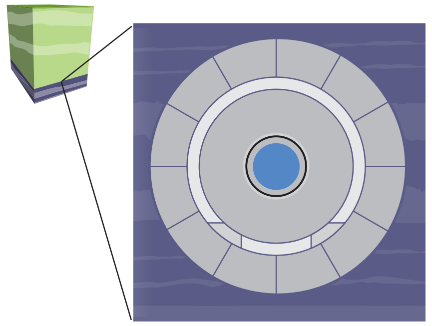
How will the disposal system evolve over time?

The information available to OPERA to quantify GDF performance is subject to different types and levels of uncertainty. OPERA allows 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 expected to be **pessimistic forecasts** of system performance. However, it is essential at the same time for system engineering optimisation purposes to make **best estimates** of how we expect the system to behave, acknowledging the uncertainties along the way. This allows a balanced view that will inform later decisions on GDF design optimisation and, eventually, on acceptable site characteristics. For example, this approach avoids over-engineering system components unnecessarily, or rejecting otherwise acceptable GDF sites.

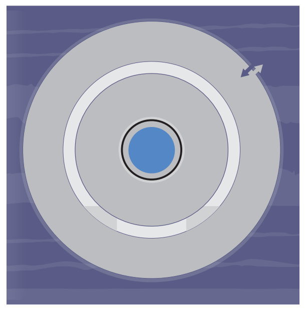
OPERA compares best estimates of the behaviour of system components in different timeframes (expected evolution) with the simplified assumptions of the safety assessment. The expected behaviour is summarised in the illustration below.

From closure to 1000 years

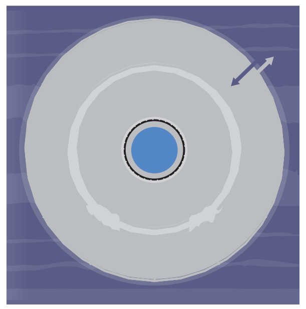
Pore spaces in the materials in the disposal tunnels will progressively become saturated with water from the Boom Clay. Over the first decades to a few hundred years, there will be a temperature gradient outwards into the clay, as the temperature due to the radioactive decay heat from the SRRF and vHLW builds up and declines. The elevated temperature and the influx of clay pore waters containing dissolved organic carbon and other solutes will promote chemical reactions leading to the localised precipitation of minerals.


supercontainer after closure

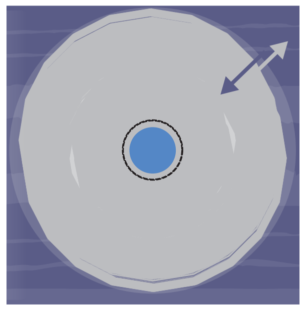
The disposal tunnel has a concrete liner for mechnical support. After emplacement of the supercontainer in the tunnels, the void space between the container and the lines are backfilled with foamed concrete.


1,000 years

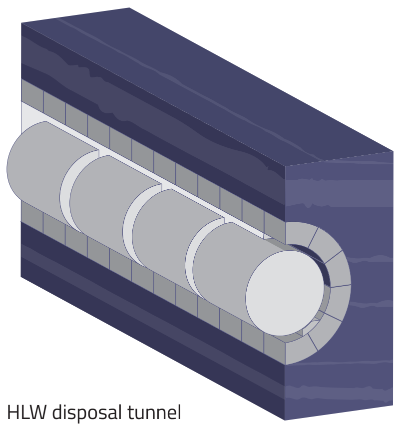
Pore water very slowly diffuses into concrete liner and cement components diffuse into clay. Slow diffusion-dominated, anoxic corrosion of the overpack has started. RRSF has cooled down, but has not come into contact with water.


10,000 years

Concrete components of the EBS undergo slow mineral transformation controlled by diffusion from and into the Boom Clay. slow diffusion-dominated, anoxic corrosion of the overpack continues. Most of short-lived radioactivity has decayed in-situ.

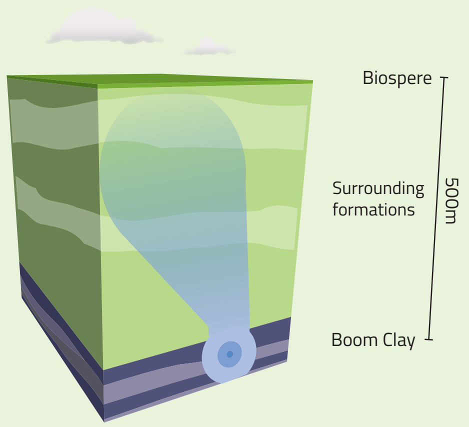

100,000 years

Concrete components of the EBS are beginning to lose their distinct identity to form a continuous mass. The majority of supercontainers maintain the containment function (intact overpack). the radiotoxicity of the RRSF is close to that of the original uranium ore.


HLW disposal tunnel

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.



The lithostatic load of the geological formations overlying the tunnels will be taken up by the tunnel liner. The concrete is expected to degrade slowly by reaction with clay pore waters, inwards from the Boom Clay / tunnel liner interface. Since the degradation will penetrate only a few tens of millimetres into the liner after 1000 years, it is unlikely that this very limited decalcification could cause the liner to begin to lose compressive strength.

The alkaline conditions in the concrete liner, backfill and supercontainer buffer will limit the amount of corrosion of the supercontainer overpack. As the steel outer shell and the overpack corrode in water under anaerobic conditions, hydrogen gas will be generated and will diffuse out of the EBS and into the Boom Clay, where it will be dispersed.

At the end of this period, it is expected that the properties and geometry of the tunnels and the EBS will have changed very little, there will be limited chemical interaction between the clay pore waters and the cementitious materials and the overpack will be mechanically and physically intact, but corroding. The initially high radiotoxicity of the SRRF and vHLW will have reduced considerably during this period of total containment. Elsewhere in the GDF, the ILW and LLW steel packages will start to corrode, possibly losing their integrity, allowing waste to begin to leach slowly.

A **simplified** behaviour is modelled in the OPERA safety assessment. In the ‘early failure’ case, all the overpack fail by a combination of corrosion and lithostatic load, exactly at 1000 years. The tunnel liner has degraded, so that the lithostatic load is transmitted directly onto the overpack, which is weakened by corrosion and fails. The load is then transmitted onto the inner canister, which also fails. At that point, vHLW begins to dissolve as it comes into contact with water. SRRF and the radionuclides it contains are dissolved instantly. Radionuclides are then free to diffuse out into the Boom Clay. The LILW containers are ‘failed’ from the time of GDF closure and all LILW groups (except depleted uranium) are assumed dissolved instantly. The uranium dissolution rate is controlled by its low solubility.

From 1000 to 10,000 years

The concrete components of the EBS are expected to undergo slow mineral transformation, leading to some loss of strength of the tunnel liner. However, the end of this period, the liner and the backfill will have undergone only very limited decalcification (tens of millimetres), which will not have penetrated the supercontainer buffer, even though the outer steel shell will have corroded through. It is possible that the tunnel liner will locally have a reduced load bearing function. Alkaline conditions in the buffer pore waters will persist, so the slow corrosion rate of the overpack steel would continue, but it is expected that all the supercontainers would retain their integrity throughout this period.

By 10,000 years, most of the short-lived radioactivity in the SRRF and other wastes will have decayed in-situ, the long-lived radionuclides will remain in (or in the vicinity of) the waste containers, and the hazard potential of all classes of HLW will have diminished considerably. That of vHLW will have become less than the uranium ore from which the (now reprocessed) fuel was originally manufactured.

The **conservative** behaviour modelled in the OPERA safety assessment ‘early failure’ case, is that all the radionuclides in the SRRF are assumed to enter solution instantly after 1000 years and be free to diffuse out into the Boom Clay. For LILW, all the containers are assumed to have failed immediately after closure of the GDF, with all radionuclides instantly released into the total porosity of the EBS. For depleted uranium, the containers are assumed to fail at 1500 years, with the release of uranium into the Boom Clay limited by its low solubility.

From 10,000 to 100,000 years

The liner, backfill and buffer are likely to begin to lose their distinct individual identity to form a more continuous mass of cementitious materials. But, modelling studies show that the inner buffer of the supercontainer in contact with the overpack will still retain its design properties. Precipitation of calcite would be advanced in the outer half of the concrete liner, which could block the porosity of the concrete, hindering diffusion. The pH in the supercontainer buffer remains high, even after 100,000 years, continuing to hinder corrosion of the overpack.

It seems probable that the majority of supercontainers would retain their containment function throughout this period. Upper estimates of corrosion lifetime for a 30 mm thick overpack are from 700,000 up to several millions of years, although it is to be assumed that some containers would have been penetrated locally by these very long times. It is possible that some supercontainers might lose their containment function towards the end of the 100,000 period, although the inner canisters would still have to corrode or collapse under the lithostatic load. As a consequence, it is expected that the vHLW and SRRF in most packages would not be exposed to leaching by porewaters within this period. Around the end of this period, the radiotoxicity of the SRRF will be close to that of the original uranium ore from which it was manufactured.

The **conservative** base failure case in the OPERA safety assessment assumes that the supercontainers all fail at 35,000 years. The ‘realistic corrosion’ case assumes 70,000 years. All the radionuclides in the SRRF are assumed to enter solution instantly at these times and be free to diffuse out into the Boom Clay. The vHLW is assumed to dissolve quickly: for the base case it dissolves and releases its radionuclides at a steady rate within 20,000 years.

Throughout this period, the EBS is allocated no containment function and all the radionuclides remaining in the waste are assumed to be free to diffuse out into the Boom Clay. Radionuclides already released into the Boom Clay are assumed to have entered the overlying sediments and be migrating towards the biosphere.

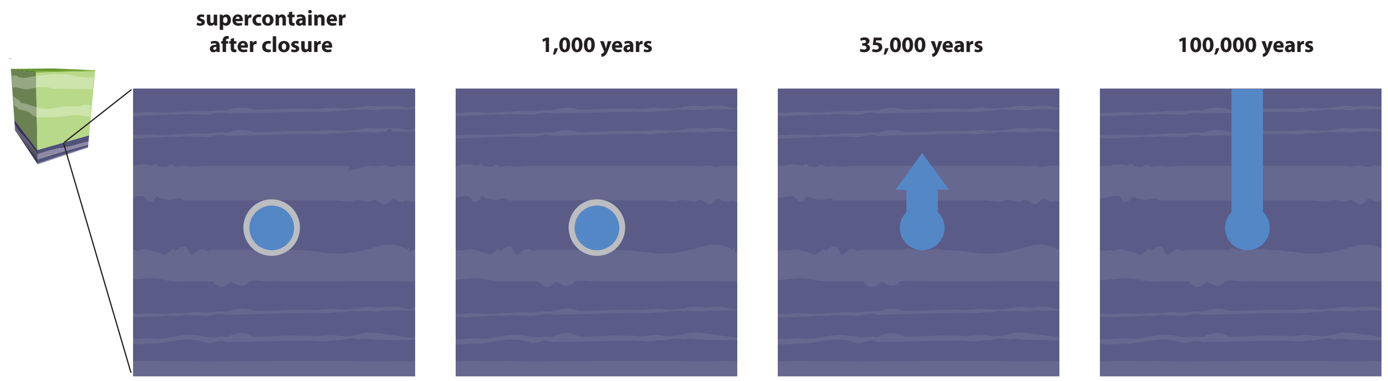
From 100,000 years to one million years

Even up to the million years, the clay host rock itself will show look little different from its original state. However, it can be assumed that both the physical strength and chemical containment functions of the concrete will have broken down completely by the end of this period. This will be a progressive process over the 100,000 to one million year timescale, with the mechanical and corrosion failure times of overpacks and inner canisters being staggered over many tens of thousands of years, so that the access of pore waters to the spent fuel and the start of release of radionuclides would be spread over long periods of time.

Mobile radionuclides will be mobilised into pore waters that enter the inner canisters and will start to diffuse through the degraded concrete into the Boom Clay. Others will enter solution extremely slowly. Many radionuclides diffuse so slowly with respect to their half-lives that they will decay to insignificance during transport though a thick clay formation. Uranium could take hundreds of millions of years to diffuse into the overlying formations.

The most mobile radionuclides will reach the aquifer system in the overlying sediments, with some being sorbed onto the sediments. Sorption, dispersion and the large delay and dilution in space and time, mean that these mobile radionuclides can reach the biosphere only in extremely small concentrations. After a million years, immobile and long-lived radionuclides will still remain within the degraded EBS. U-238, the main component of depleted uranium, will remain within the GDF until the inexorable processes of geological erosion over hundreds of millions of years disperse it into new sediments and rocks. It will behave like a naturally occurring ore body.

In contrast, the **conservative** safety assessment models forecast that, with the exception of the long-lived uranium series radionuclides, practically all radioactivity that has not decayed will have migrated out of the Boom Clay and been dispersed into the sediments and the biosphere within a few hundreds of thousands of years.



After closure of the repository the EBS consists of concrete (liner, backfill, buffer supercontainer), a steel overpack and the HLW inside.

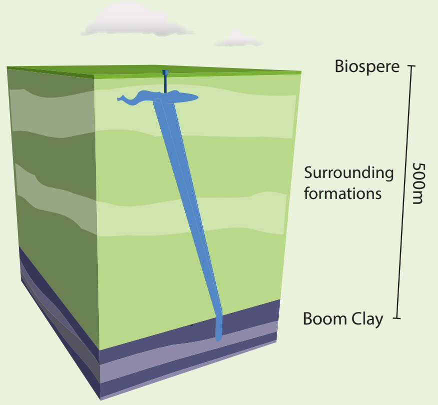
Until the moment of container failure, the containment of the EBS remains intact and no migration of radionuclides takes place.

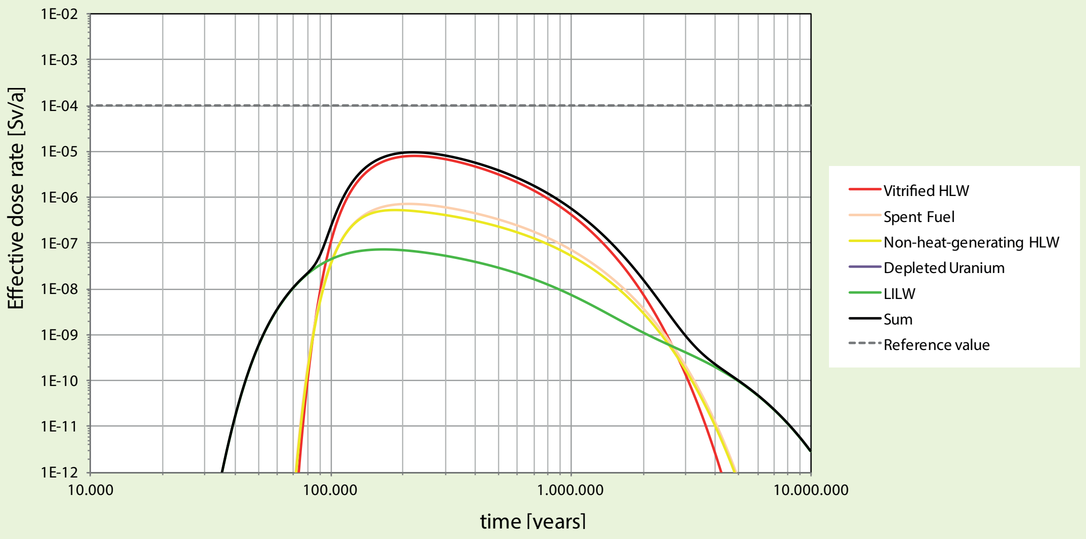
After failure of the container, The HLW instantly dissolves and diffuses into the Boom Clay, except for vitrified HLW, where the glass starts to dissolve gradually releasing the radionulides.

Even after a 100,000 years, only a very small fraction of the radionuclides has left the Boom Clay and entered the surrounding formations.

100,000 - 1,000,000 years

The wastes that dominate the calculated exposures are vitrified HLW and SRRF, even though the volumes of these wastes 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 selected for OPERA (0.1 mSv per year) and about 150 times lower than average natural background radiation exposures.





The illustration below summarises the simplified behaviour modelled in the OPERA safety assessment over each of the periods discussed above and can be compared with the previous illustration of expected behaviour.

How safe is the OPERA GDF?

The OPERA safety assessment calculates the potential impacts of the GDF on the environment over the timescales discussed. The results are compared with indicators and reference values used for judging the performance of the disposal system and its overall safety. The assessment model splits the geological disposal system into compartments, evaluating radionuclide behaviour within each and calculating transfers between them.

The biosphere acts as the receptor for any radioactivity that moves upwards from the geosphere. OPERA models biosphere processes that determine how people might be exposed to radionuclides from the GDF. 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.

OPERA models 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. 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 a 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 GDF into the biosphere is another useful reference value; it can be compared to that from radionuclides naturally present in the overburden entering the biosphere.

The Normal Evolution Scenario

The Normal Evolution Scenario (NES), along with sensitivity analyses of some key parameters, is the reference case for this initial stage of OPERA. Future work will evaluate additional cases and scenarios.

The figure below presents the calculated radiation doses to individuals as a function of time after GDF closure, for all the wastes in the GDF, using the conservative case of 'early failure' for the supercontainer at 1000 years. It shows the contributions of each waste family to the effective dose rate, aggregated for all radionuclides. Depleted uranium is not visible because its contribution to the calculated dose is so low that it is below the scale of the figure.

The wastes that dominate the calculated exposures are vHLW and SRRF, even though the volumes of these wastes 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 exposure value selected for OPERA and about 250 times lower than average natural background radiation exposures in the Netherlands.

The supercontainers hold the largest fraction of the radioactivity in the GDF and contain it completely until their allocated time of failure. In the base case of the NES, this occurs at 35,000 years, at which time all the supercontainers are pessimistically assumed to fail together and all of the radioactivity in them to become instantly available to enter porewaters and diffuse out into the Boom Clay. From this time onwards, the bulk of the calculated total radiotoxicity in the system resides in the Boom Clay. About a tenth of the total radiotoxicity resides in the depleted uranium, which is still within the GDF, 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 Boom Clay and the GDF. As expected in this geological disposal concept, the Boom Clay represents the principal and most influential barrier in the multibarrier system.

A key observation is that, within a few hundred thousand to a million years, almost all the radioactivity initially in the GDF has either decayed within the GDF or the Boom Clay; only a tiny fraction has migrated out to be diluted and dispersed in the overlying formations and biosphere. The GDF has effectively performed its isolation and containment task by this time.

The exception to this picture is depleted uranium, which, although it comprises more than half the mass of the waste materials in the GDF, contains only about 0.2% of the total radioactivity at the time of disposal. Its principal radionuclide (naturally occurring U-238) has a half-life that is so long 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 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, but that 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.

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 from natural sources of radioactivity. Also, they would not occur until many tens or some 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.

Can the disposal system be optimised?

Optimising the radiological protection provided by the GDF is an important objective for the future. In OPERA, optimisation options examined have as yet been limited to evaluating different containment periods in the supercontainer. For slow release rates and a very long containment time in the supercontainer, the calculated peak exposure is little reduced, only being pushed further out into the future, so there appears to be little advantage in using a much thicker overpack, if peak dose is the main concern. However, these conclusions are based only on the NES and other evolution scenarios have not yet been studied in OPERA.

Conclusions of the initial OPERA Safety Case

What is the feasibility of constructing the GDF?

The OPERA GDF concept is based on the well-developed Belgian GDF design for Boom Clay, but its construction is proposed to be at about 500 m, twice the depth of the Belgian underground research facility in the Boom Clay. This increases the isolation provided by the geological environment but also presents increasing engineering challenges. Geotechnical assessment within OPERA indicates that a stable and robust GDF can be engineered and operated at this depth, but more needs to be known more about the nature and variability of Boom Clay properties and about the in-situ stress regime on a regional basis across the Netherlands to refine the current outline concept.

Existing tunnelling techniques using a tunnel-boring machine can be used to excavate the GDF. The working design will need to be refined and optimised progressively, as more information on the Boom Clay becomes available. Construction and operational feasibility at the assumed depth depend on using a heavy-duty tunnel lining and support system. There are options for the types of cement and concrete that can be used for the EBS; this will allow tailoring and optimisation of the GDF design in the future. Overall, there is considerable scope to adapt and optimise the engineering design of the GDF over future years and it is expected that the eventual design (if Boom Clay is chosen as the host rock) will be significantly further developed from the OPERA concept.

What does OPERA say about the feasibility of siting the GDF?

OPERA was not a siting study, but it is important to have confidence that suitable locations for a GDF might be available if Boom Clay is eventually selected as the host formation. Boom Clay is present in appropriate thicknesses and depth range across large parts of the NW and SE Netherlands, but there are significant uncertainties in its depth-thickness distribution. Data on Boom Clay properties at 500 m are sparse and need to be considerably improved.
The eventual GDF design can be adapted to be compatible with the specific properties of many candidate locations, thus allowing flexibility in depth and layout aspects that are not critical to safety.

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 Boom Clay properties, and regions that show evidence of past deep glacial erosion.

Future development of the concept will depend on obtaining better data on the Boom Clay at depth, as well as on regional hydrogeological and geomechanical properties of overlying formations. This will require access to boreholes and samples from relevant disposal depths. At the current programme phase, boreholes do not represent the commencement of a siting programme, but rather a scientific approach to achieving broader validation of some of OPERA's 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 and other Paleogene formations, including the Ypresian Clay.

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 OPERA GDF provide adequate safety?

The GDF concept provides complete containment and isolation of the wastes during the first few hundreds to a few thousand years when 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 GDF will be contained by the Boom Clay 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 confidence in safety

Natural and archaeological analogues of materials' preservation 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 below) 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 2000 year preservation of Roman iron objects in similar anoxic conditions (see image below) supports the OPERA assumptions on the minimum longevity of the supercontainer overpack. Roman cements and concretes show that the massively cement-dominated OPERA 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 the GDF. 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 performance 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. For example, they are closely comparable with the impacts calculated for the proposed Belgian GDF, also in Boom Clay.

Improving the design and the Safety Case

A number of processes and scenarios that could affect or alter the NES have not yet been treated at this stage of OPERA and thus constitute open issues that will require further R&D and safety assessment. The principal uncertainties have been identified in each OPERA work package and will be addressed by future OPERA studies. Not all of the work is required in the next decades, but will be staged over several iterations of the future OPERA programme.
Overall conclusions of OPERA

Over the six years of its operation, OPERA and has achieved its principal aims and has been a valuable exercise to progress and support national policy in the Netherlands. A GDF in the Boom Clay at around 500m depth can clearly fulfil its task of permanently isolating Dutch wastes and protecting current and future generations.

The results obtained to date give confidence that the disposal of all the current Netherlands inventory of long-lived and highly active radioactive wastes at depth in the Boom Clay is feasible.
The approach evaluated is sufficiently flexible to handle any likely future inventory changes, or respond to changes in disposal schedule.

The OPERA GDF concept, if implemented at a site with an appropriate geological setting, is capable of providing high levels of safety that match those estimated in other national programmes. It would clearly meet international standards for this type of facility. Predicted radiation exposures of people are extremely small, far below exposures to natural background radioactivity and would not occur until tens or hundreds of thousands of years into the future. The quality of drinking water in terms of its content of radiotoxic elements will not be affected today or in the future.

More work remains to be done, however, and continued RD&D will enhance and optimise the GDF design, giving a clearer picture of future costs and implementation flexibility. OPERA has built upon CORA, which built upon OPLA, and it is essential to maintain continuity of expertise and knowledge amongst the scientific and technical community in the Netherlands.

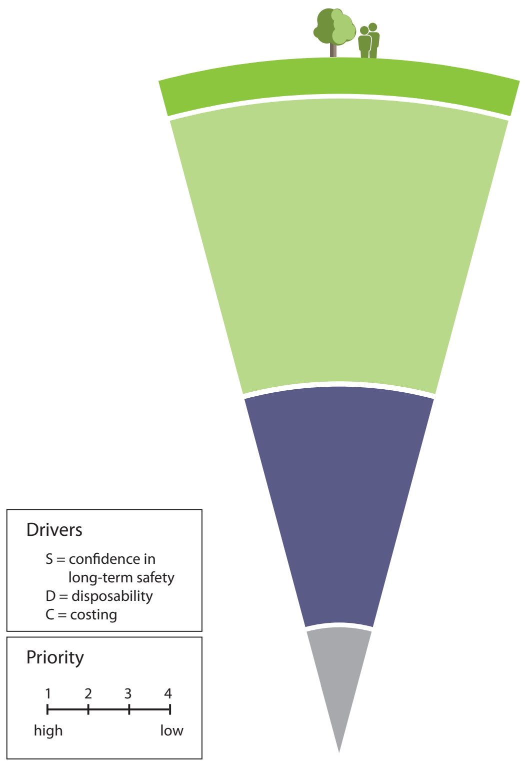
Future work will involve desk studies and laboratory testing and experiments. However, it is also recommended that some deep geological sampling and testing is carried out in the near-future to provide a firmer basis for future work. This is perhaps the greatest area of technical uncertainty in the OPERA work to date.

OPERA has focussed on the Boom Clay: salt formations and other clay formations are also options for a GDF. Salt has been explored in the past and would merit an equivalent exercise to OPERA in the near future. Much of the information and many of the approaches developed in OPERA are directly transferrable to evaluation of these other formations.

Looking forwards

The information generated in OPERA can be used to support waste management policy development in the Netherlands and to provide a more accurate basis for establishing future financial provisions for waste management. In particular, the availability of a safety assessment reference case and approach allows COVRA to make disposability assessments of any future waste arisings or packaging proposals from waste producers.

The OPERA results are compatible with the policy decision to provide long-term storage and carry out a staged programme of RD&D into geological disposal: they effectively show that an end-point of geological disposal exists and can be implemented. OPERA has developed a roadmap for this future RD&D that starts with the identification of the key topics that need to be addressed in future work. The illustration below shows these key topics for the



Drivers
S = confidence in long-term safety
D = disposability
C = costing

Priority

Component	Key topics	Drivers	Priority
Society	Integrating societal aspects into technical research	S ■■■ D ■□□ C ■□□	2
Biosphere	- (Current knowledge sufficient)	S ■□□ D ■□□ C ■□□	4
Surrounding rock formations	Salinity in deeper ground water model Effect of climatic change	S ■■□ D ■□□ C ■■□	3
Host rock	Geotechnical properties Diffusion dominated transport Retardation Long-term evolution	S ■■■ D ■■□ C ■■■	1
Engineered barrier system	Concrete evolution Waste package design Tunnels and galleries	S ■■□ D ■■■ C ■■□	2

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 Boom Clay.

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 Boom Clay, but more data need to be collected on its properties and their variability at relevant depths.

The existence of the OPERA project 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.

Major projects such as OPERA have been completed in the past, but there has been no continuity to maintain expertise. This situation needs to be avoided and OPERA provides a strong launching point for a planned programme of technology maintenance and transfer within Netherlands organisations, national knowledge management for the future, and continued cooperation with national and international waste management initiatives.

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