SUMMARY COPERA SALT 2024

A CONDITIONAL SAFETY CASE AND FEASIBILITY STUDY

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Summary

The objective of this report is to present an overview of results and conclusions of the on-going work in the Netherlands on developing safety cases for a Geological Disposal Facility (GDF). COPERA is COVRA's ongoing long term research programme expected to run for decades and includes research for GDFs in poorly indurated clay, rock salt and multinational solutions. The COPERA 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 research programme has a structure that can be used for several programming periods; each decade will result in an iteration of two safety cases, one for GDF in rock salt and another for a GDF in poorly indurated clay. The present report documents the latest safety case for a GDF in rock salt; it has been prepared in parallel with a second iteration of the safety case for a GDF in clay.

The national context of the geological disposal programme, the wider than usual range of objectives and the wide target readership, means that there are significant differences between the report presented here and recent national Safety Cases published in other countries. The COPERA Salt 2024 Conditional Safety Case & Feasibility study is, for example, less comprehensive, given that it is an initial analysis that will be followed by further iterations. On the other hand, the report is wider in scope than many other national Safety Cases. Explanatory material has been included, for example, to describe the basic concepts involved in geological disposal and to summarise the current international consensus on the recognized approaches to achieving safety and to structuring a technical Safety Case for a GDF. This is done to make the report accessible to a wide readership. In addition, proposals for future scientific and technical studies have been developed, using the information gathered during the preparation of the Safety Case. These are presented in a roadmap, laying out all COVRA's ongoing activities leading eventually to implementing a GDF in the Netherlands.

We are, however, fully aware that a successful GDF programme must address both societal and technical issues, as well as scientific and technical matters. Globally, the greatest obstacles to the geological disposal of waste have been related to gaining sufficient public and political support for the concept itself and, more specifically, for siting activities. The Rathenau Institute has explored a society-based approach to identifying potential siting areas and locations for a GDF.

What's new in COPERA

The structure of the COPERA project focuses on development of safety cases for rock salt and clay repositories. The present report documents an Initial, Conditional Safety Case for rock salt: this also gives a framework for future planning.

An updated disposal concept has been produced for the Geological Disposal Facility (GDF) – with an engineered barrier concept including a waste package specifically designed for the disposal of the most active wastes.

Developments in other countries considering deep disposal in rock salt have been fully integrated: in particular, there has been close cooperation with both the disposal programmes in Germany and the United States. Both these countries have repositories in rock salt.

COVRA is developing a Requirements Management System (RMS) that will structure all 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, considering the need to be compatible with the parallel safety case in poorly indurated clay, and also with COVRA's waste storage programme.

The cost estimate for a GDF in rock salt has been updated based on demonstrated construction and emplacement techniques from both the disposal programmes in Germany and the United States.

Based on the results, priorities and specific goals have been developed for work in the next phase of the COPERA research programme.

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 always ensures safety and security. For materials that remain hazardous up to hundreds of thousands of years, the recognised approach to long-term isolation and confinement is disposal in a GDF constructed in a stable geological environment far beneath Earth's surface.

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, although this might change. The extended timescales allow flexibility in case alternatives to disposal in a national GDF become available; one such option is disposal of Dutch waste in a shared, multinational repository.

COPERA is COVRA's current, on-going long-term research programme that started in 2020. COPERA is not the first Dutch programme on geological disposal. It builds on predecessor programmes, OPLA (1985 - 1992), CORA (1995 - 2001) and OPERA (2010 – 2017).

The focus of this COPERA salt 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. As in the previous programme OPERA, 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 COPERA programme in the Netherlands.

The development of scientific and technical understanding, data and arguments that support this 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?

Three scenarios for future waste arisings were developed in 2022 as part of the national programme. Waste Scenario 1 is identical to the scenario used in OPERA: the operation of the Borssele Nuclear Power Plant until 2033 and the replacement of the High Flux Reactor in Petten with Pallas. The expected eventual inventory of wastes from all sources destined for geological disposal in Waste Scenario 1 is shown in Table 1. The design of the GDF in rock salt presented here can be easily adapted to the other 2 waste scenarios, provided that their waste characteristics match those used in waste scenario 1.

Waste Scenario 1 - Current installations +

Type	Volume in storage (m^3)	Number of canisters / containers in storage	Number of canisters / containers for disposal	Volume for disposal (m^3)
200 L drums	38,141	100,000	100,000	31,461
1000 L Containers		8,400	8,400	
Decommissioning waste	3,814	-	826	3,814
(TE)NORM	49,360	-	12,600	58,070
CSD-c	90	502	84	504
CSD-v	86	478	80	530
ECN-cansiter	49	244	122	643

Table 1) The expected number of waste packages for disposal in Waste Scenario 1.

What could a Dutch geological disposal facility look like?

The GDF design developed for COPERA (2020 – 2025) 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.

The repository described here is assumed to be constructed in a salt dome: a massive body of salt that can extend a few kilometres in both the vertical and horizontal direction. The repository consists of surface and underground facilities, connected by three vertical shafts (Fig. 1). To make optimal use of the vertical extent of a salt dome, the underground facilities are at two levels for different categories of waste. The upper and lower levels are located at depths of about 750 and 850 m below the surface: depths chosen to ensure that deep erosion (glacial channels) will not disturb the repository during a future ice age. Both levels have an infrastructure area, with the larger, main infrastructure area located at the upper level. The upper-level infrastructure includes a mechanics workshop, material depot, personnel break rooms, equipment for dose rate measurements and decontamination, storage areas for vehicles, vehicle workshop, battery loading room, electricity supply room, transformer station, surveyors' office and bunker for backfill. The smaller, lower level infrastructure area is used to store equipment that is needed on a day-to-day basis at that level. In addition to the shafts, there is an inclined spiral ramp that connects the upper with the lower level. A minimum thickness of about 200 m of rock salt around the waste is considered sufficient to provide an adequate principal natural barrier. In the generic salt dome upon which the current concept is based, there is 350 m of salt surrounding the waste, which is 150 m more than the assumed minimum.

The lower level is for the disposal of vitrified high-level waste (vHLW), spent fuel from research reactors (SRRF) and non-heat-generating high-level waste (HLW). Here, most radioactive wastes are encapsulated in HLW packages optimized for disposal in rock salt (Fig. 2). These are thick-walled, carbon steel (TStE335) containers to hold the various types of HLW canisters, and have a thickness of 220 mm, as shown in Figure 2: For ECN canisters for SRRF on the left for and CSD-v and CSD-c canisters for vitrified HLW and fuel assembly debris on the righ. The upper level is for the disposal of low and intermediate level waste (LILW) and depleted uranium.

How do we analyse the safety of the GDF?

Quantitative analysis of the safety of the GDF is the central theme of this Safety Case. Estimates of potential radiological impacts on people are described for various future scenarios of how the disposal system might evolve. The Normal Evolution Scenario (NES) is the central case considered; it assumes normally progressing, undisturbed construction, operation and closure of the GDF, with no significant external disturbance of the disposal system in the future. However, the COPERA safety assessment recognizes that there are uncertainties about the long-term behaviour of some parts of the disposal system, as well as the potential for the GDF to be affected by various natural or human-induced processes and/or events, about which there are also some uncertainties. These uncertainties might perturb the normal evolution of the GDF and need to be assessed. One of the most important natural scenarios to consider is major climate change, which could lead 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 the distant future. Accordingly, COPERA also identified other types of scenarios, including a range of alternative evolution, some of which are addressed in the COPERA safety assessment - failure of the HLW packages directly after closure of the repository, failure of all tunnel seals, failure of a spiral ramp seal, less probable characteristics of radionuclide mobilization and transport, and reduced long-term sealing by backfill. Others will be addressed in a future assessment - failure of a shaft seal, flow path between a brine pocket and nearby mine excavations, pressure-induced permeation of fluids in salt formations. In addition, three different

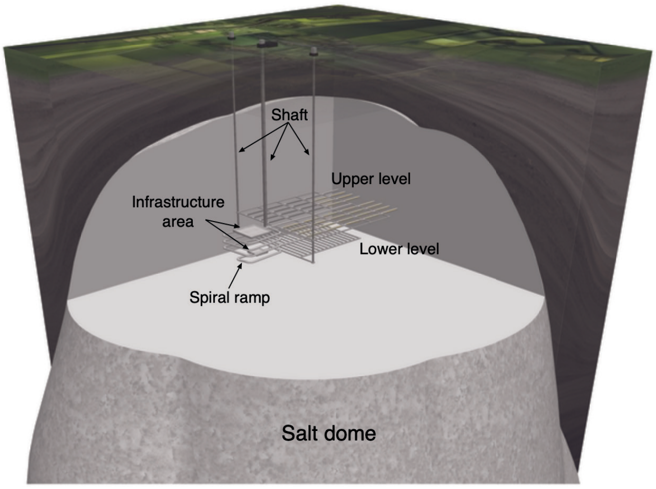


Figure 1) The general layout of a two-level repository in a generic salt dome. The upper level will be used for the disposal of LILW and (TE) NORM while the lower level will be used for the disposal of HLW.

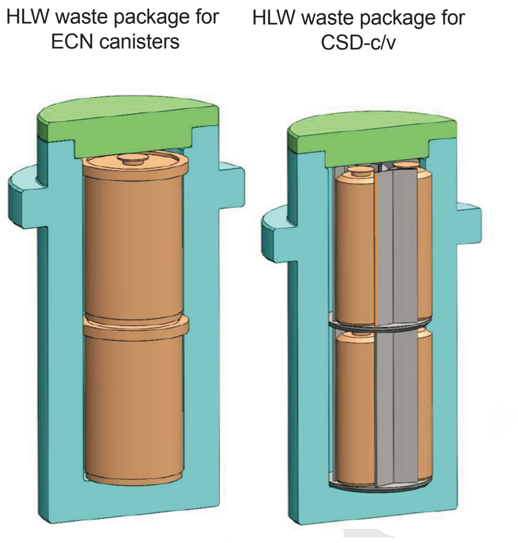


Figure 2) The two designs of HLW package. Left: the HLW package for 2 ECN canisters. Right: the HLW waste package for 6 CSD-c/v canisters.

human intrusion/influence scenarios have been identified and these will also be addressed in a future assessment.

For each of the scenarios considered, the potential future evolution of the GDF system is assessed, based on detailed studies needed to understand how each component will perform in the short and long term. Using this information, the migration of radionuclides that may be released from the wastes in the GDF is modelled and the impacts of any releases to the biosphere is calculated.

How much will the GDF cost?

The GDF design and the proposed implementation process allow estimates to be made of the future costs that will be incurred. These estimates determine the financial contributions to be paid by current waste producers to ensure that the national waste fund will be sufficient for GDF implementation. The total costs for disposal in 2130, based on the timetable, are estimated to be 3.5 billion Euro. The cost estimate assumes that a definitive decision on the disposal method will be made around 2100. An underground observation phase of 10 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 is 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 45 years on the concept of the multibarrier system, whereby a series of engineered and natural barriers act in concert to isolate and contain the wastes and their hazardous content (Fig. 3). The relative contributions to the safety of the various barriers at different times after the 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.

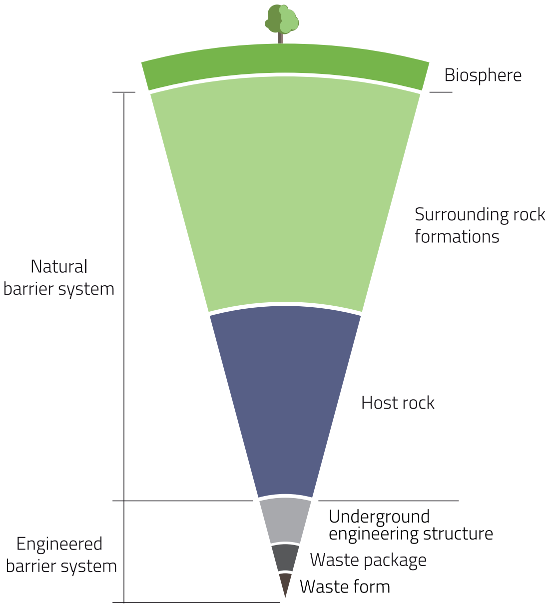


Figure 3) Components of multibarrier systems at the time of completion and closure of the geological disposal facility.

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, rock salt, and the overlying geological formations comprise the natural barriers within the multibarrier system.

Rock salt is the principal natural barrier. Undisturbed rock salt is practically impermeable and can thus provide complete containment. In the Netherlands, deposits of rock salt are very old and stable. Rock salt from the Zechstein Group, for example, was deposited over 250 million years ago during the Permian, while the rock salt in the Triassic Röt formation is over 145 million years old. Both have the capability to isolate the waste from people and the environment for at least the one million year timescale examined in safety assessments and probably for much longer, and both are present in a potentially appropriate depth range across large parts of the northeast and southeast Netherlands, in thicknesses of greater than 200 m. While COPERA considers a GDF in a generic salt dome, with some minor changes, the repository could also be constructed in other salt structures, such as bedded salt and salt sills. Bedded salt formations have a roughly horizontally layered structure, while a salt sill is an intermediate form between bedded and dome salt.

Because salt is plastic, deforming under load, and soluble in water, diapirism and subrosion are processes that must be assessed when considering the long-term stability of a formation. Diapirism is the gradual upward movement of a salt dome through overlying sedimentary formations, while subrosion is the dissolution of salt by groundwater. In principle, these processes could lead to the disruption of the geological barrier (salt) around the GDF and release of radionuclides into groundwaters over timescales of millions to tens of millions of years. However, these timescales are long after the hazard potential of the wastes has diminished, and well beyond the period of concern for safety assessment. In the Netherlands, diapirism rates of salt domes are estimated to be between 0.001 and 0.1 mm/year and possibly even lower, while the subrosion rates are estimated to be in the order of 0.01 and 0.1 mm/year and possibly even lower.

It is recognised that there are uncertainties related to the properties of the rock salt and that these need to be studied in the future. Three areas of uncertainty are currently considered, namely the thickness and depth of salt formations of potential interest for a GDF, their internal structure and homogeneity, and their short- and long-term evolution. The quality and coverage of the data on the thickness and depth of the rock salt of the Zechstein group and the Röt formation (the two most promising formations for a GDF) are not yet high enough to allow proper consideration of potential siting areas. This is particularly the case for the Röt formation. There is also a large uncertainty in the internal structure and homogeneity of salt structures in the Netherlands, in part because it is challenging to image salt structures seismically and interpret the data. With respect to the long-term evolution of salt structures, the subrosion and diapirism rates have been determined for specific salt domes in this and previous research programmes but are not precise. Better data would help to improve understanding of the evolution of salt structures through time. With respect to short-term evolution (tens to hundreds of thousands of years), the specific interest is on how major climate driven changes such as an ice age could influence the diapirism and subrosion rate.

Overlying and underlying geological formations

The bedded and dome salt formations of the (late Permian) Zechstein Group and the Röt formation lie within a thick sequence of sedimentary formations. Depending on location, this can range from salt deposits of the middle Permian Rotliegend Group,sandstones and conglomerates of the Early Triassic Germanic Triassic Group, salt of the Muschelkalk and Keuper formations and clay in the Upper North Sea Group. Some of the sediments in the overburden have high permeability and act as aquifers, through which radionuclides could potentially migrate to the surface if they were to leave the repository. These aquifers contribute to post-closure safety because any releases that might occur would be dispersed and diluted in these large bodies of groundwater, 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 the present country has been covered by ice. Ice-sheet loading can affect subrosion and diapirism rates and glacial meltwaters at the end of an ice age can cause deep erosion. In a future GDF siting programme, it will be essential to look in more detail at the likelihood and consequences of such a scenario. The current understanding is that interglacial conditions similar to the present day are likely to persist for around 100,000 years – possibly longer. If deep erosion does not affect a GDF until sometime after 100,000 years, the radioactivity of the HLW will already have been markedly reduced.

The current COPERA safety assessment makes the conservative assumption that the next ice age will occur much sooner, in 50,000 years' time.

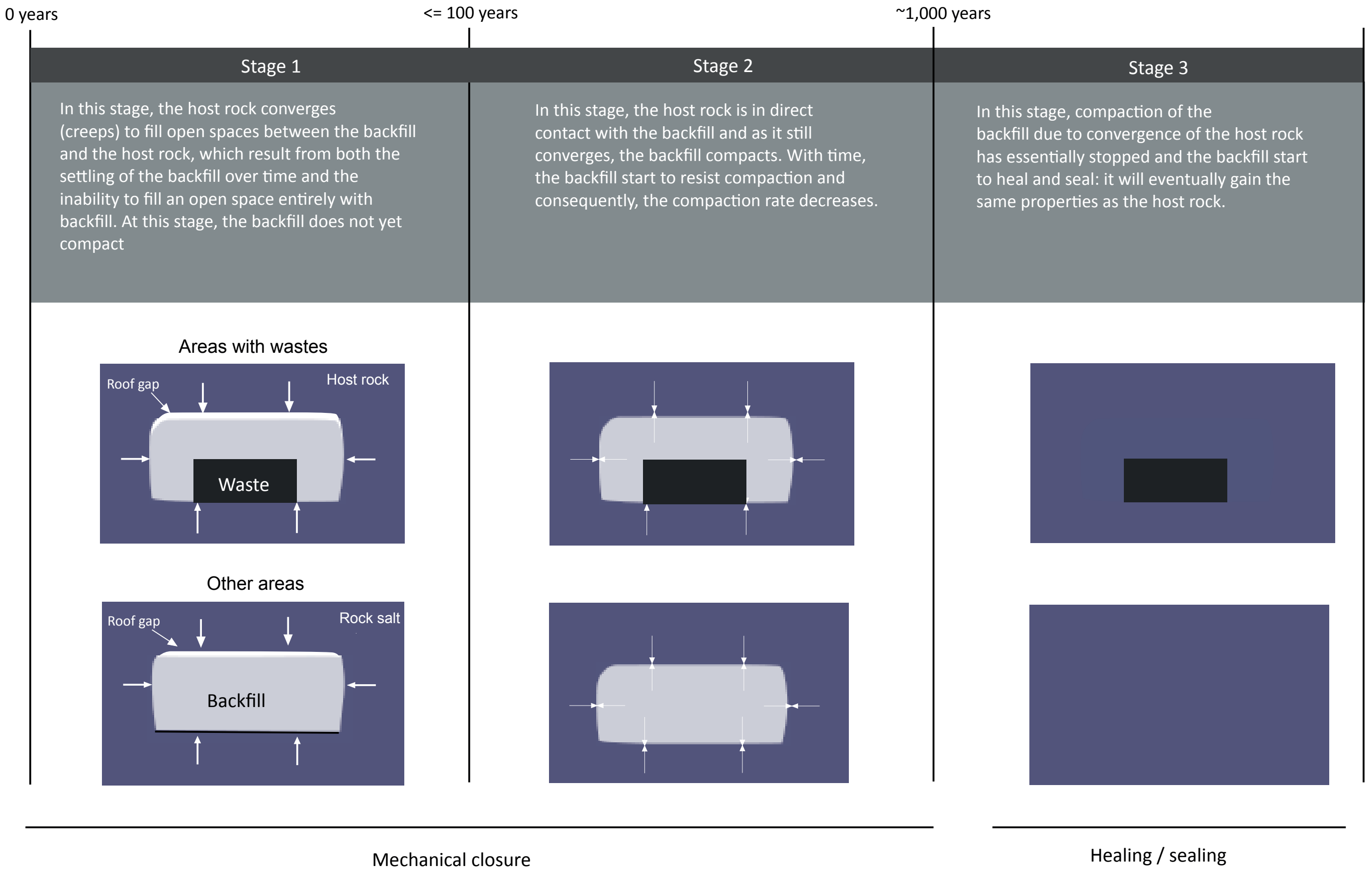
What is the Engineered Barrier System?

Undisturbed rock salt is practically impermeable and should thus, on its own, provide complete containment. Construction of the repository, however, perturbs the host rock by excavating shafts, tunnels and other open spaces needed to emplace the wastes. To ensure the closure and sealing of these open spaces, multiple engineered barriers are used. These are concrete backfill and seals, granular salt backfill, the HLW package and the HLW and LILW waste forms themselves, along with their containers. For the various types of HLW, engineered containment after closure of the GDF is initially provided by the steel HLW package (Fig. 2) and the concrete seals in the shafts and disposal tunnels that prevent the inflow of water from overlying formations. For the various forms of LILW, containment during the operational period is provided by the waste forms, their containers, concrete seals and the cement backfill of the disposal rooms, but after closure of the GDF, our safety case currently (and conservatively) assigns no containment function to their waste forms, containers and the cement backfill of the disposal room.

It is expected that the initial engineered containment barriers of the HLW (waste package, seals) will degrade with time and additional engineered containment must be provided, in the form of granular salt backfill. This backfill is in any case an important component of the engineered containment during the operational and immediately post-closure stages, as it stabilises the openings in the GDF. This because it is used to backfill the transport, ventilation and service tunnels in the upper and lower level, as well as the shafts, between the concrete seals. Granular salt backfill initially has a relatively high porosity and permeability but, compacts with time, so that its properties becomes comparable to the undisturbed host rock: impermeable. In the HLW disposal tunnels it is emplaced dry, to limit corrosion of the HLW packages and the production of gas but is moistened during emplacement where it is used in the shafts and other openings within the lower and upper level (e.g., transport, service and ventilation tunnels), as this increases the compaction rate to ensure it achieves the required low permeability faster. In the unlikely case that brine inflow to the waste occurs, the engineered barriers contribute to the containment of the radionuclides by restricting the movement of contaminated brine or allowing only very slow dissolution and mobilisation of the radionuclides. For backfilling the infrastructure areas in both the upper and lower level, gravel will be used. This is done to help to minimise the gas pressure within the repository: within the gravel, gas can accumulate if it is generated.

How will the backfill and seals behave in the multibarrier system?

Granular salt backfill is a key component of the salt GDF multibarrier concept and contributes to the long-term containment function of the repository system by achieving a very low permeability by compaction. Three successive stages of compaction can be recognised (Fig. 4). In the first stage, the host rock converges (creeps) to fill open spaces between it and the backfill; these result from both the settling of the backfill over time and the inability to fill an open space entirely during backfill emplacement. During this phase, the backfill begins to self-compact and microcracking may occur within the host rock closest to the tunnel, in the so-called excavation disturbed zone (EDZ). In the second stage, the backfill starts to compact more strongly, due to stress imposed by the convergence of the host rock, since both are now in direct contact. The rate at which the backfill compacts depends on many factors including, for example, intrinsic properties such as the grainsize of the backfill, the temperature and the moisture content, but also the rate of convergence of the surrounding host rock, coupled with the resistance of the backfill. Under repository conditions, it is expected that stages 1 and 2 take in total about 1,000 years for a moisturised granular salt backfill. At that point, the granular salt backfill will have a permeability of about $1 \cdot 10^{-19}$ m^2. In the third stage, compaction of the backfill has essentially ceased. At this point, static healing/sealing of both the granular salt backfill and the EDZ in the host rock is expected to become the dominant process; this will eventually result in the granular salt backfill attaining the same properties as the host rock: it will become impermeable. Dry granular salt backfill will take much longer to reach stage 3 but will only be used in tunnels where HLW will be disposed of, to minimise gas generation.



In this stage, the host rock converges (creeps) to fill open spaces between the backfill and the host rock, which result from both the settling of the backfill over time and the inability to fill an open space entirely with backfill. At this stage, the backfill does not yet compact

In this stage, the host rock is in direct contact with the backfill and as it still converges, the backfill compacts. With time, the backfill start to resist compaction and consequently, the compaction rate decreases.

In this stage, compaction of the backfill due to convergence of the host rock has essentially stopped and the backfill start to heal and seal: it will eventually gain the same properties as the host rock.

Figure 4) The three different stages of compaction and healing/sealing affecting the HLW disposal tunnels, and the dominant processes involved. During the first stage, convergence of the host rock closes the crown-space gap. In the second stage, the granular backfill compacts. Stages 1 and 2 together are referred to as mechanical closure. In Stage 3, compaction due to convergence of the host rock has ceased and the backfill starts to heal and seal.

For the COPERA safety assessment, we conservatively consider only the second of the three compaction stages mentioned. The first stage is not modelled, as it is expected to last for only a few decades so that the initial state of the disposal system assumed in the safety case is reached almost immediately. The third stage is not modelled at present, as it is still part of ongoing research. Thus, in the COPERA safety assessment, the assumption is that compaction will stop when a residual porosity of 1% is reached and the associated permeability is about $1{\cdot}10^{-19}\,m^2$. This is a conservative assumption, as it is expected that the porosity will decrease further due to healing and sealing (stage 3; disconnection of pores in the salt) which in turn will decrease the permeability even further, until the granular salt backfill becomes impermeable.

It is recognised that there are uncertainties related to the compaction of the granular salt backfill – most importantly, how long it takes to attain the same properties as the host rock (stage 3). Better understanding of this will help to refine our requirements and optimise the other concrete and steel engineered barriers. A further uncertainty that needs to be quantified relates to the minimum thickness of the granular salt backfills in the shafts between the GDF tunnels and the top of the salt dome. Finally, the effect on compaction of gases generated by corrosion processes in the repository needs further investigation.

In the period when the granular salt backfill still has a high permeability, the necessary containment is provided by strategically placed seals in both tunnels and shafts. The moisturised granular salt backfill is expected to obtain a low permeability in about 1,000 years. However, the concrete seals are expected to maintain their effectiveness for much longer: 50,000 years. After this period, it is assumed that glaciation may alter hydrogeological and geochemical conditions, introducing significant uncertainty in predicting the chemical composition of incoming waters which could lead to the degradation of concrete seals—particularly those in direct contact with the overburden formations. Based on practical experience in Germany, there are two current options for tunnel seals: Sorel and salt concrete.

A simplified shaft design is assumed in COPERA as the eventual shaft design will depend on the local geology (e.g., the presence of anhydrite layers). The simplified closure system, where it passes through the rock salt, consists of, from top to bottom, a concrete seal, moisturised granular salt backfill and a further concrete seal. Detailed shaft seal designs have not been considered in any of the previous Dutch studies on rock salt, but work has been done elsewhere. Extensive research in both Germany and the USA has yielded a design that consists of different elements that, together, provide the necessary short and long-term properties to ensure containment. The proposed shaft sealing for the Gorleben repository in Germany, for example, consists of three short-term sealing elements, one long-term sealing element, abutments, and materials that can trap water or gas in their pores. Together, these would delay the inflow of groundwater into the repository sufficiently long for the shaft granular salt backfill to gain a sufficiently low permeability. The type and thickness of the materials used depend on the structure, properties and mineralogy of the evaporite formations through which a shaft passes. It should be noted that these seals are designed only for the part of the shaft that is located within the salt: in the overburden formations, the shaft is backfilled conventionally. Further work will be required on the design of shaft closure system and seals, and on the appropriate materials to use in the seals themselves.

How will the waste packages behave in the multibarrier system

Conservatively, only the HLW package is assigned a post-closure containment role: LILW containers are assumed to provide no containment after closure of the GDF. The HLW package is designed to provide complete containment for at least 1,000 years, which is the time the granular salt backfill needs to attain a low-enough permeability to ensure that there is no significant brine flow. However, it is likely that the HLW package will provide containment for a significantly longer period. In the COPERA safety assessment, the HLW packages are assumed to fail 1,000 years after closure but an additional alternative scenario was assessed in which the HLW packages are assumed to fail directly after the closure of the repository.

For all the waste packages used for LILW and depleted uranium, an effective zero ‘failure time’ for all LILW waste packages is used in the safety assessment and COPERA conservatively assumes that radionuclides are released into the concrete backfill of the disposal rooms immediately after the closure of the GDF.

What happens to gases produced in the GDF?

As part of the COPERA research programme, a scoping study was undertaken to estimate the potential for gas generation within a repository in rock salt. Gas pressure can delay, or even halt, the compaction of the granular salt backfill. The study considered three main gas generation mechanisms: corrosion, microbial breakdown of organic substances and radiolysis (can be important in waste with high beta/gamma activity). The model results suggest that gas generation depends primarily on the availability of brine, which is likely to be very limited, not only because a repository in rock salt is dry, but also due to the low permeability of the granular salt backfill. Limiting the availability of brine reduces gas generation significantly, but some gas is likely to be generated within the GDF, because there will be some brine available, for example, in the granular salt backfill. The next step will be to expand the model to include the compaction of the granular salt backfill in the safety assessment model.

How will the disposal system evolve over time?

The information available to COPERA to quantify GDF performance is subject to different types and levels of uncertainty. COPERA allows for this by making conservative simplifications, assuming poor performance, using pessimistic parameter values and omitting potentially beneficial processes. The results of the COPERA safety assessment are thus expected to be pessimistic forecasts of system performance. However, it is also essential for system engineering optimisation purposes to make best estimates of how we expect the system to behave in reality, 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 or rejecting otherwise acceptable GDF sites.

COPERA 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 below.

From closure to 1,000 years

It is expected that the characteristics of the biosphere and the overlying sediments remain similar to the present day, with only some minor erosion, which will not affect the repository's performance. After the repository is sealed, the (moisturised) granular salt backfill in the tunnels and shafts will begin to compact, reducing porosity and permeability over the next 1,000 years, thereby effectively sealing the repository. The heat generated by high-level waste (HLW) will temporarily speed up the compaction process, while any small fractures in the surrounding rock will heal during this period.

Within the repository, brine displacement will occur as the granular salt backfill compacts, but the flow will be limited due to its low brine content and the low permeability of the backfill. In the first 1,000 years, radionuclides from LILW and (TE)NORM will primarily be transported through advection, but after this period, diffusion will become the dominant mode of transport. HLW radionuclides will remain fully contained within the HLW packages.
Gas generation from corrosion of the steel HLW packages and radiolysis will be minimal, as the granular salt backfill surrounding the HLW packages has no added moisture: in other placer moisture is added to the granular salt backfill to increase compaction. In addition, any gas generated will migrate to areas of the repository that do not compact. These are the infrastructure areas that will be backfilled with gravel and the concrete seals. After 1,000 years, the moisturised granular salt backfill will have attained a low permeability within the lower and upper levels and stage 2 of compaction will end. This is followed by the healing and sealing of the backfill (stage 3). In contrast, dry granular salt backfill used in the tunnels with the HLW packages will still be in stage 2 as its compaction is significantly slower. Also in the shaft, the moisturised granular salt backfill will still be in stage 2 at the end of this period as the temperature and pressure are lower than in the upper and lower levels of the repository and hence the compaction is slower.

In terms of subrosion and diapirism, 0.1 m of salt will have been removed by subrosion and the salt dome will have risen 0.1 m at the end of this 1,000 year period. In both cases, the current subrosion and diapirism rate of 0.1 mm/year is assumed.

A simplified behaviour is modelled in the COPERA safety assessment. It is assumed that the HLW packages will remain intact during this period, while LILW packages are assumed to provide no containment and consequently LILW radionuclides are assumed to be released immediately after the repository's closure. Temperature and lithostatic pressure, which influence backfill compaction, are considered constant, with temperatures based on a geothermal gradient and pressure calculated from the sediment and salt density at the Gorleben site. Conservatively, no solubility limits are included, and the granular salt backfill will remain permeable throughout this period. Gas generation is not considered in this assessment but will be addressed in the next safety evaluation.

1,000 years after closure – start next glacial period (assumed at around 50,000 years)

As for the first 1,000 years, the biosphere, including climate, vegetation and groundwater, are expected to remain similar to present day conditions, though sea levels may fluctuate. Subrosion, which will continue at the current rate of 0.1 mm/year, will result in about 5 m of salt being dissolved at the end of this period. Likewise, with a rate of 0.1 mm/year assumed here, the depth of the repository will decrease by 5 m due to diapirism. It is assumed that the next ice age will occur in 50,000 years which is, as a result of global warming, unlikely. Subrosion, diapirism and changes in the biosphere are not expected to affect the repository's performance. Within the repository, moisturized granular salt will start to heal and seal (stage 3) within the lower and upper levels. Moisturized granular salt used in the shaft will still be in stage 2 at the start of this period but after a few hundred more years it will also start to heal and seal (stage 3). In contrast, the dry granular salt in the disposal tunnel will take an additional several thousand years to reach this stage. As healing progresses, the pores in the backfill will disconnect, preventing diffusion and effectively immobilizing any mobilised radionuclides within the granular salt backfill. Additionally, no water will be able to enter the repository via the shaft, ensuring the full containment of radionuclides.

In the safety assessment, it is conservatively assumed that the HLW package will fail 1,000 years after repository closure. At this point, radionuclides from the CSD-v, CSD-c and ECN canisters are considered instantly available for transport. Furthermore, the granular salt backfill is assumed not to heal in the safety assessment, so advective and diffusive transport of radionuclides remains possible, though very limited and slow due to the low permeability of the granular salt backfill. Additionally, gas generation is considered zero.

Next glacial period (duration assumed to be 100,000 years)

This period covers the next ice age, during which several geological changes are expected. The uppermost 50 m of sediment may erode, rivers could incise by 20 - 120 m, and glacial basins up to 150 m deep may form. As an ice sheet advances over the salt dome, differential loading could temporarily increase diapirism rates. Permafrost may penetrate up to 270 m underground, reducing groundwater recharge, increasing salinity and slowing subrosion. However, glaciations will lower the sea level, increase groundwater flow velocities and raise subrosion rates. The movement of the ice sheet could also reactivate old faults, temporarily increasing their permeability. Melting ice sheets may force fresh water into overburden sediments, further increasing subrosion rates, while glacial channels up to 600 m deep may form and fill with sediment.

By this time, compaction of all the granular salt backfill in the repository will have reached the final stage, with properties equivalent to those of the host rock, thereby immobilizing all radionuclides within the GDF. Over a 100,000-year ice age, the salt dome is expected to rise by 10 m, with an equal amount of salt dissolving due to subrosion: in other words, the repository itself is still too deep to be affected by an ice age. The total amount of salt dissolved by subrosion at the end of this stage is 15 m. The salt dome will have risen by the same amount.

In the safety assessment, it is conservatively assumed the granular salt backfill still has sufficient permeability to allow both advective and diffusive transport of radionuclides. Furthermore, gas generation is assumed to be zero.

End of the glacial period – 1,000,000 years

The next stage covers the period from the end of the first ice age to one million years. During this time, multiple glacial periods could occur, potentially forming multiple glacial channels and increasing subrosion and diapirism rates temporarily. These glacial periods could significantly change the biosphere and reduce the overburden formations above the repository, possibly bringing it closer to the surface, especially if sedimentation does not occur. At most, 10 glacial periods might be expected to occur within one million years, with varying durations and intensities. Only some of these might be expected to extend far enough south to affect the Netherlands. Moreover, sedimentation is expected to continue, increasing the thickness of the overburden, and no major tectonic events are anticipated that would result in regional uplift of the Netherlands. While the future development of the overburden formations is uncertain, it is improbable that the salt dome will pierce the surface: the repository is expected to remain several hundred meters deep.

Within the repository, conditions are therefore expected to remain stable, with the backfill maintaining the same properties as the host rock, and all radionuclides remaining contained. Over one million years, about 100 m of salt will dissolve due to subrosion, assuming a 0.1 mm/year, leaving at least 250 m between the repository and the top of the salt dome. Even in a scenario with double the subrosion rate, there would still be 150 m of separation. Diapirism will cause the repository to rise by 100 m at the end of this period, assuming a diapirism rate of 0.1 mm/year. Hence, neither subrosion nor diapirism will affect the repository's performance.

On even longer time scales, subrosion and diapirism may eventually release small amounts of immobile, long-lived radionuclides into overburden formations. By then, the repository's hazard potential will be comparable to, or lower than, naturally occurring ore bodies.

In the COPERA safety assessment, as for the previous periods, advective and diffusive transport of radionuclides can still occur during this period. As in the previous period, no gas generation is expected.

How safe is the GDF?

The COPERA safety assessment calculates the potential impacts of the GDF on the environment over the timescales discussed above. It takes a simple and largely conservative modelling approach that adopts a similar methodology and assumptions to those of other international exercises. The approach captures the widely accepted, most critical processes of advection, diffusion and compaction that control the behaviour of a GDF in salt.

The Normal Evolution Scenario

The Normal Evolution Scenario (NES), is the reference case for this initial stage of COPERA. The safety assessment shows that even after a million years remain in place within the repository: no radionuclides have migrated out of the repository into overlying formations and biosphere. The multibarrier system has effectively performed its isolation and containment task by this time. Over much longer periods, many millions of years, releases are likely to occur eventually in the normal evolution scenario in locations where there is a significant combined effect of subrosion and diapirism, if these rates are high. However, by such times the hazard potential of the waste has reduced to levels well below those of natural uranium ore deposits.

Overall, even using pessimistic approaches, the performance assessment calculations for the NES show that potential radiation exposures to people in the first million years after closure are zero. The NES is the most likely evolution and remains the focus for calculations in the far future. Long-term interactions between degradation products of the different types of waste are limited, since the different types of waste are disposed of at different sections of the GDF. These interactions need, however, to be evaluated. Also, gas generation needed to be included in future post-closure safety assessments, as it could slow down or even hinder compaction, or impact other processes.

In conclusion, in the normal evolution scenario, and for at least one million years after closure, what is placed in salt stays in salt.

The Alternative Scenarios

Alternative evolution scenarios are less likely but it is important to calculate their consequences because these calculations show the redundancy of the multibarrier system. In total, five of eight identified alternative scenarios were modelled in the COPERA safety assessment. These are failure of all HLW packages directly after the closure of the repository, failure of all tunnel seals directly after the closure of the repository, failure of a spiral ramp seal directly after the closure of the repository, less probable characteristics of radionuclide mobilization and transport, and reduced long-term sealing by backfill. Although differences exist in the extent to which radionuclides travel within the repository for each alternative scenario, in no cases are radionuclides predicted to leave the repository within one million years after closure. The results indicate that the shaft seals play an important role in long-term safety by limiting the amount of brine entering or leaving the repository. Future work will evaluate the remaining alternative scenarios and human intrusion scenarios.

Can the disposal system be optimised?

Optimising the radiological protection provided by the GDF is an important objective for the future. In COPERA, examination of optimisation options has been limited, especially as the release in the normal evolution is zero. However, the safety assessment shows that the designs of the HLW package, tunnel seals and spiral ramp seal do not affect the outcome of the safety assessment: these are not critical factors for the safety concept. This is because the shaft seals, when they function as expected, inhibit any contaminated brine from entering or leaving the repository. Nevertheless, using a robust HLW package has advantages, in particular during the operational period, when it eases handling. Likewise, the use of tunnel seals also has operational advantages, and may also play a critical role should the shaft seals not function as expected, although this needs to be tested.

A potential cost optimisation is the reduction of the centre-centre distance between HLW packages. In the current disposal concept, this is 10 m, but could be reduced to allow for more HLW packages within a disposal tunnel. However, its effect is expected to be limited. Another potential optimisation is to use the depleted uranium waste as an aggregate in concrete, which is then used as a backfill material. A further option would be to use the conditioned depleted uranium directly as a backfill for the disposal rooms used for the disposal of LILW. Irrespective of where it is used, the time needed for disposal of all the waste would be reduced by ten years, and 21 fewer disposal rooms would be needed, thus reducing to less than half the number of upper-level disposal rooms. However, the impact on sealing effectiveness of using concrete with depleted uranium as an aggregate is not yet well studied. In addition, backfill containing depleted uranium must be treated as a radioactive material, which complicates operations

Conclusions of the initial COPERA Salt 2024: A Conditional Safety Case & Feasibility study

The feasibility of constructing a GDF in salt in the Netherlands

The COPERA GDF concept is based on the well-developed German concept for disposal of HLW in salt domes and on the operational WIPP repository in bedded salt in New Mexico, USA. It also builds on the previous Dutch concepts. There are decades of practical experience in both commercial salt mining and even in constructing an actual repository for radioactive wastes.

Geotechnical assessment within the COPERA research programme indicates that a stable and robust two-level GDF can be constructed and operated in a salt dome at depths of >700 m, with the model adopted for COPERA having levels at 750 and 850 m depth. For the construction of the GDF, existing salt mining techniques and equipment (e.g. continuous miners and scalers) can be used.

Existing international studies also show that there are practical techniques for sealing tunnels and shafts in a GDF. It is expected that further progress and operational experience will become available over the next 100 years, well before these techniques need to be deployed in the Netherlands.

Overall, there is considerable scope to adapt and optimise the engineering design of the GDF in future years and it is expected that any eventual design will be significantly further developed from the current COPERA concept.

The feasibility of siting a GDF in salt in the Netherlands

COPERA was not a siting study, but it is important to have confidence that suitable locations for a GDF might be available if rock salt is eventually selected as the host formation. Rock salt is present in appropriate thicknesses and depth ranges across large parts of the northeast and north of the Netherlands, but there are significant uncertainties in the depth-thickness distribution of some rock salt formations. Also, the internal structure of salt structures, in particular of salt domes, is not yet well known. The eventual GDF design can be adapted to be compatible with the specific properties of 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 considered include other uses to which a salt dome might have been subject (e.g., the presence of caverns for storage of oil, gas et cetera), the variability of the rock salt properties, the potential for deep glacial erosion and diapirism and subrosion rates.

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 Paleogene clays for which a safety case is presented, in parallel to this report.

It is recognized 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.

The COPERA salt GDF provides a completely safe disposal solution

The GDF concept is expected to provide complete containment for at least 1 million years and possibly for much longer. Beyond this period, a minute fraction of highly mobile radioactivity might eventually, due to disruption of the geological barrier by subrosion or diapirism, move into surrounding geological formations, but will be diluted and dispersed in deep porewaters and groundwaters, resulting in biosphere concentrations that cause no safety concerns and are expected to be well below natural levels of radioactivity in drinking water.

Confidence in safety

The safety case for geological disposal relies on understanding processes that have been active for millions of years in deep rock formations. By studying geological settings similar to those considered for a GDF, we can gain confidence in our understanding of these processes. Natural analogues provide evidence of rock salt's ability to offer long-term containment. For instance, the existence of 250-million-year-old rock salt indicates its impermeability, as any permeable salt would have been dissolved by groundwater. Examples include gas trapped beneath the Zechstein salt in the Netherlands and CO_2 trapped in the Werra/Fulda salt deposit in Germany, which demonstrate rock salt's effectiveness as a seal.

Additionally, rock salt's dryness leads to exceptional preservation of organic materials. In the Hallstatt salt mines, artefacts from the Bronze Age, including wooden tools and textiles, have been preserved. Similarly, ancient human remains found in the Chehrabad Salt Mine in Iran are remarkably well-preserved due to the dryness of the salt.

For understanding the compaction of granular salt backfill, analogues are crucial, since laboratory experiments can only simulate short time periods and may not accurately reflect real conditions. The Sigmundshall mine in Germany, where granular salt (halite) waste has compacted to low porosity over 40 years, provides insights into the compaction process. The findings from this mine indicate that pressure solution creep is a significant mechanism at low stresses and must be considered when determining the time-scales for sealing backfilled repositories in rock salt - as is done in the COPERA safety assessment.

Confidence in the reliability of the COPERA performance assessment calculations is also enhanced by the fact that they are compatible with those estimated independently by other national programmes and also in previous Dutch rock salt safety assessments.

Optimisation of the design and the Safety Case is possible

Several processes and scenarios that could affect or alter the normal evolution have not yet been treated at this stage of COPERA and thus constitute open issues that will require further R&D and safety assessment. The principal uncertainties have been identified in each COPERA work package and will be addressed by future studies. Not all the work is required in the next decades; it can be staged over several iterations of the future COPERA research programme.

Over the five years of its operation, COPERA has achieved its principal aims and has been a valuable exercise to progress and support national policy in the Netherlands. A GDF in the rock salt at around 750 m 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 rock salt is feasible. The approach evaluated is sufficiently flexible to handle any likely future inventory changes or respond to changes in disposal schedule.

The COPERA GDF concept, if implemented at a site with an appropriate geological setting, can provide high levels of safety that match those estimated in other national programmes. It would clearly meet international standards for this type of facility. However, more work remains to be done and continued RD&D will enhance and optimise the GDF design, giving a clearer picture of future costs and implementation flexibility. COPERA has built upon OPERA, which built upon CORA and OPLA, and it is essential to maintain continuity of expertise and knowledge amongst the scientific and technical community in the Netherlands in this way.

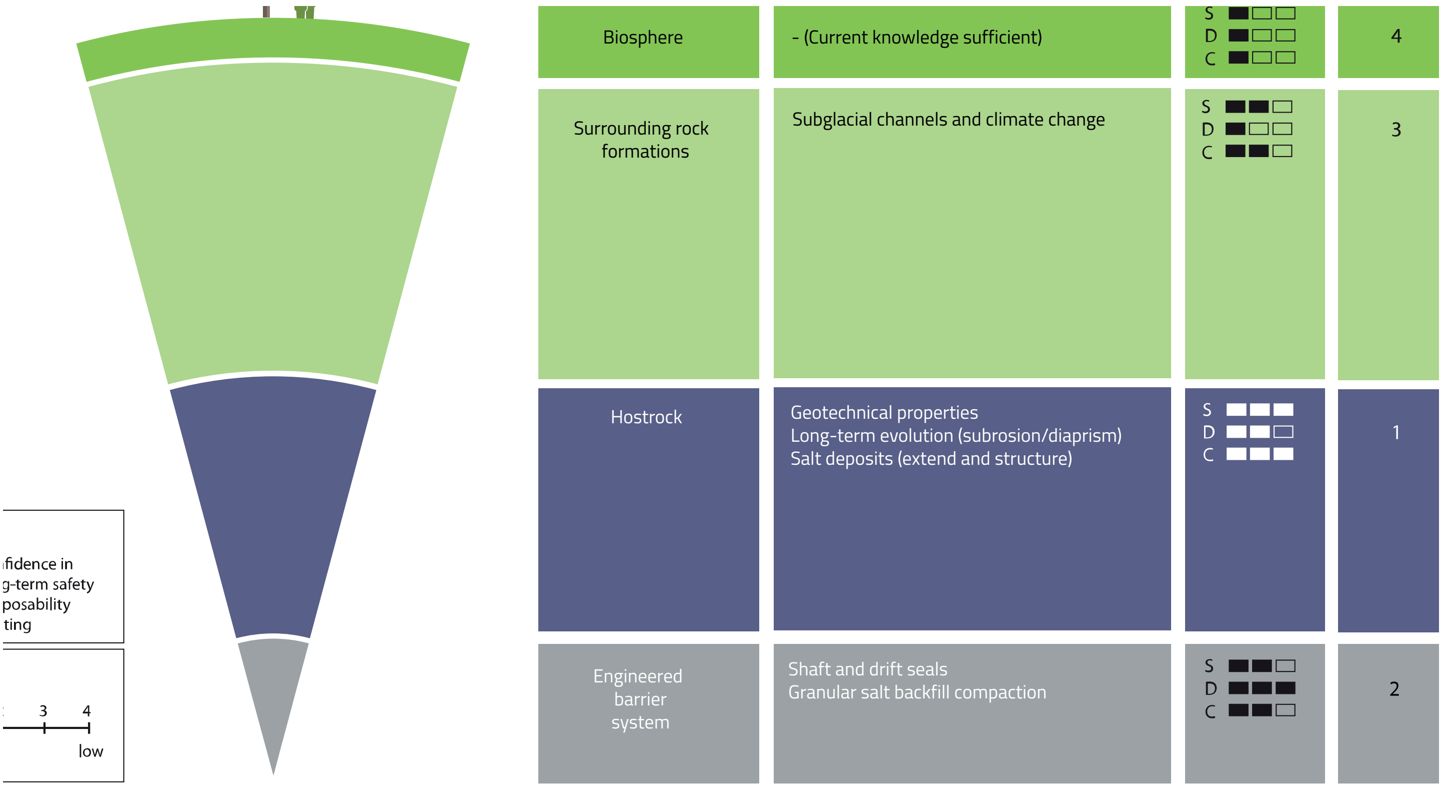
Looking forwards

The information generated in COPERA 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. The availability of a safety assessment reference case and approach allows COVRA to make disposability assessments of any future waste arisings or of packaging proposals from waste producers.

The COPERA results are compatible with the policy decision to provide long-term storage and to carry out a staged programme of research, development, and demonstration (RD&D) into geological disposal. They illustrate that an endpoint of geological disposal can be implemented. COPERA has developed a roadmap for future RD&D for disposal in rock salt that starts with the identification of the key topics that need to be addressed in future work. The illustration below (Figure 5) 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 host rock: rock salt.

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.

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 multi-national projects.



Biosphere	- (Current knowledge sufficient)	S ■□□ D ■□□ C ■□□	4
Surrounding rock formations	Subglacial channels and climate change	S ■■□ D ■□□ C ■■□	3
Hostrock	Geotechnical properties Long-term evolution (subrosion/diaprism) Salt deposits (extend and structure)	S ■■■ D ■■□ C ■■■	1
Engineered barrier system	Shaft and drift seals Granular salt backfill compaction	S ■■□ D ■■■ C ■■□	2

Figure 5) Key topics for research into geological disposal in salt, organised according to the components of the multi barrier system.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This report presents a summary of the results and conclusions of the Safety Case for a geological disposal facility in Permo-Triassic salt of 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.

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