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The principal objective of this report is to present an overview of the results and conclusions of the Safety Case for a geological disposal facility in the Boom Clay of the Netherlands. The present 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. A separate, complementary synthesis report deals with the wider, societal issues of disposal. The work has been performed in the framework of the OPERA research programme which also includes some further research topics and these are also mentioned. The principal objectives of OPERA were:

- To examine the feasibility and long-term safety of a Geological Disposal Facility (GDF) in the Boom Clay of the Netherlands
- To strengthen the national competences in scientific and technical areas related to geological disposal
- To select - using a structured process - the R&D activities to be carried out in the Dutch disposal programme over the coming years
- To inform politicians, the public and the scientific/technical community about the progress of geological disposal planning in the Netherlands.

OPERA is financed by the Dutch authority for nuclear safety and radiation protection (ANVS) and the public limited liability company Electriciteits-Produktiemaatschappij Zuid-Nederland (EPZ) and coordinated by COVRA. The present report is an overall summary of the achievements of the OPERA programme. COVRA acknowledges all the researchers from Dutch and foreign research organisations that have contributed to OPERA. It was decided at the outset to structure the programme and the future work around the development of a series of Safety Cases for a GDF in the Netherlands; this approach is in line with common international practice. Accordingly, the report is labelled as an Initial Safety Case. However, because of the national context of the geological disposal programme in the Netherlands, and because of the wider than usual range of objectives and the correspondingly target readership, there are significant differences between the Initial Safety Case presented here and GDF safety cases from other countries, which have often been prepared in order to meet some specific permitting or licensing requirement.

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. Because of this, the Netherlands has benefited greatly through the close cooperation which has been possible with the Belgian waste disposal programme, in which comprehensive investigations on Boom Clay as a host rock have been in progress for many years. However, the option of disposal in salt is still open, and significant earlier work has been done in the Netherlands on this potential host rock. In any case, no siting decisions will be taken in the Netherlands for a long time into the future, so that the next generation of safety cases whether in clay or in salt will continue to be generic in nature.

On the other hand, the present report is wider in scope than many other safety cases for two reasons. Firstly, because of the wish to make the report accessible to as wide a readership as possible, 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 on the structure of a technical Safety Case for a GDF. Secondly, additional information is included on the overall scope of the OPERA programme since the current report is intended to summarise also the structure of the R&D projects which underpin OPERA. Finally, proposals for future scientific and technical studies which have been developed using the information gathered in the process of safety case preparation are presented at the end of the current report in a roadmap laying out all COVRA’s activities leading eventually to implementation of a GDF in the Netherlands. COVRA is willing to receive any comment readers might have.
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.

<table>
<thead>
<tr>
<th>Waste Category</th>
<th>In storage (2130)</th>
<th>Packaged for disposal (2130)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume [m³]</td>
<td>Weight [tonne]</td>
</tr>
<tr>
<td>Processed LILW</td>
<td>45000</td>
<td>150000</td>
</tr>
<tr>
<td>Depleted uranium</td>
<td>34000</td>
<td>110000</td>
</tr>
<tr>
<td>Vitrified HLW</td>
<td>93</td>
<td>191</td>
</tr>
<tr>
<td>Spent research reactor fuel</td>
<td>104</td>
<td>99</td>
</tr>
<tr>
<td>Other HLW</td>
<td>256</td>
<td>600</td>
</tr>
</tbody>
</table>

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 milestone in the Dutch radioactive waste management programme, the report also covers other research performed in the framework of the wider OPERA research programme.

OPERA has initiated work on communication with the Dutch public, including stakeholder engagement and conditions for an inclusive synthesis report deals with the wider, societal issues of disposal, to which this report is a contribution. A separate, complementary programme must address both technical and societal issues.

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.
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. 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 multibarrier system can function in different ways 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. 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 measured over large distances 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
How will the waste containers behave in the GDF? Conservatively, the only container assigned a post-closure containment role is the inner steel liner of the HHU/SF supercontainer. This prevents access of porewaters to the waste for as long as it can maintain mechanical and early thermal stresses and resist failure under 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 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 requirements on the basis of the evaluation of the results of the current or future OPERA assessments. The Konacl 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 ULLW 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 ULLW 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 in pore waters. Cementitious materials 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 the rate of all radionuclides into EBS pore waters upon failure of the overpack.

Concrete components of the EBS undergo slow mineral transformation controlled by diffusion from the Boom Clay. Slow diffusion-dominated, anoxic corrosion of the overpack has started. SRRF has cooled down, but has not come into contact with water.

Concrete components of the EBS are beginning to lose their distinctive identity to form a continuous mass. The majority of containers maintain the containment function intact (outpack). The radioactivity of the SRRF is close to that of the original uranium ore.

How will the disposal system evolve over time?

The interation 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 pore clay waters containing dissolved organic carbon and other solutes will promote chemical reactions leading to the localised precipitation of minerals.
The lithostatic load of the geological formations overlying the tunnels will be taken up by the tunnel liner. The concrete is expected to degrade immediately after closure of the EBS, and all radionuclides instantly released into the total porosity of the EBS. 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. Percolation 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 vHLL and SRRF in most packages would not be exposed to leaching by porewaters within this period. Around the end of this period, the radioactivity 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 radio- nuclides in the SRRF are assumed to enter solution instantly at these times and be free to diffuse out into the Boom Clay. The vHLL 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 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 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 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 occurring body. In contrast, the conservative safety assessment models forecast that, with the exception of the long-lived uranium series radio- nuclides, 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.

<table>
<thead>
<tr>
<th>Time</th>
<th>Effect (x 10^-15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 - 1,000,000 years</td>
<td>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.</td>
</tr>
<tr>
<td>100,000 - 1,000,000 years</td>
<td>The waste that dominates the calculated exposure is 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.</td>
</tr>
<tr>
<td>100,000 years</td>
<td>After closure of the repository, the EBS consists of concrete (liner, backfill, buffer supercontainer), a steel overpack and the HLW in the supercontainer. The EBS instantly dissolves and releases its radionuclides, where the glass starts to dissolve gradually releasing the radionuclides.</td>
</tr>
<tr>
<td>10,000 years</td>
<td>After failure of the container, the HLW instantly dissolves and releases its radionuclides, where the glass starts to dissolve gradually releasing the radionuclides.</td>
</tr>
<tr>
<td>35,000 years</td>
<td>Until the moment of container failure, the containment of the EBS remains intact and no migration of radionuclides takes place.</td>
</tr>
<tr>
<td>100,000 years</td>
<td>Even after a 100,000 years, only a very small fraction of the radionuclides has left the Boom Clay and entered the surrounding formations.</td>
</tr>
</tbody>
</table>
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 radiactivity that moves upwards from the geosphere. OPERA models biosphere processes that determine how people might be exposed to radionuclides from OPERA and to other sources of natural background radiation.

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 total radioactivity in the system resides in the Boom Clay. About a tenth of the activity that is contained within the Boom Clay and the GDF. The calculated potential radiation dose to an individual is compared to its low mobility, is expected to remain within the geological formations; by the time of peak releases to the biosphere, almost all the radioactivity initially in the GDF has migrated out to be diluted and dispersed in the overlying geological formations and biosphere. The GDF has effectively performed its isolation and containment task by this time.

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

The calculations show that the GDF provides adequate safety.

Improving the design and the Safety Case

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

Does the OPERA GDF provide adequate safety?

The 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 cemented-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 the Netherlands, is not a factor in the safety case. It is recognised by COVRA that siting a GDF involves considerably more than evaluating technical factors. Any future siting programme will need to take account of societal requirements and will be staged, progressive and consensual in nature.

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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 potential hazard 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 perovskers and groundwater, 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

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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 cemented-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 the Netherlands, is not a factor in the safety case. It is recognised by COVRA that siting a GDF involves considerably more than evaluating technical factors. Any future siting programme will need to take account of societal requirements and will be staged, progressive and consensual in nature.

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.
assessments. 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 near 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 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.

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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 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.
1.1 Why do we need geological disposal?

Nuclear technologies are used in electricity generation, medicine, industry, agriculture, research, and education. As a consequence, radioactive wastes are generated; all of these wastes must be managed in a way that ensures safety and security at all times. Radioactivity naturally decays over time, so that safety can be achieved by ensuring that the wastes are isolated from the human environment until they no longer pose a hazard. The period of time for which the wastes must be isolated depends on the type of waste. It can range from a few days for very short-lived waste to more than 100,000 years for some of the long-lived waste.

The necessary levels of isolation are achieved in a first phase by containing the radioactive materials in safe and secure storage facilities. Storage of radioactive waste in surface facilities for periods up to many decades is a proven safe technology and is applied globally. Nonetheless, this storage method is not a long-term or final solution for wastes that remain radioactive for very long times and for which the necessary continued active monitoring and inspection, security and maintenance cannot be assured. 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, deep enough beneath the surface of Earth to exclude disruptions due to near-surface processes and events. This is referred to as emplacement in a Geological Disposal Facility (GDF). Geological processes in the deep underground occur at slow and predictable rates over very long periods of time. At the current state of science and technology, geological disposal is the only solution that can ensure no radioactivity will ever return to the human environment at concentrations that can be harmful.

1.2 The Dutch Context

For this above reasons, the Netherlands, along with other countries with significant quantities of long-lived radioactive wastes, has chosen geological disposal as the official national policy. The decision-in-principle to dispose of Dutch radioactive waste in a GDF was taken by the government in 1984, [VROM, 1984: p.5]. The Dutch policy is for more than thirty years based the above-ground storage of the radioactive waste for a period of at least 100 years, after which disposal deep below ground is foreseen around 2130. The definitive decision on this disposal method will be taken around 2100. As it is not possible to predict with any certainty what the best means of managing radioactive waste will be when it becomes time to reach a decision in 2100, or what then social thinking will be the policy provides a certain flexibility in terms of timetable [ANVS, 2016]. This choice is determined by the facts that waste inventories accumulate slowly, facilities ensuring safe surface storage for decades have been implemented, and a long period allows time for the build-up of the funds needed for implementation of a GDF. Furthermore, the extended timescales allow flexibility in case other options other than disposal in a national GDF become available. One such possibility is the disposal of Dutch waste in a shared, multinational repository. The Netherlands also keeps this option open; R&D activities taking place within...
In the geological disposal of radioactive wastes, it has been used widely for over two decades, both in national programmes and in the safety cases for in-use facilities. The Dutch Safety Case is clearly of this conditional nature. The currently most widely accepted description of a safety case for geological disposal is that formulated by the IAEA in 2011 and reproduced in the 2013 IAEA update. The concise definition used in OPERA is based on the IAEA Safety Standards for Geological Disposal (IAEA 2011a). “The safety case is an integration of arguments and evidence that describe, explain, and substantiate the level of confidence in the safety of the geological disposal facility”.

In Chapter 3, more details are given on the structure of a safety case and on the specific application of international guidance in the OPERA programme. In the context of the present report, several key additional generic points concerning safety cases can be made, and their relevance to the Dutch case explained:

- **Safety cases are made at various stages in a repository development programme**, so that an iterative process is necessary. OPERA represents the first iteration of a safety case for a GDF in the Boom Clay of the Netherlands. This is done by structuring the document in the form of a Safety Case, as is recommended by international bodies and their relevance to the Dutch case explained:

- **A safety case is fundamentally a risk assessment**, to resolve outstanding scientific, technical and societal issues, and to develop progressively the disposal project for Dutch waste. It will be necessary to develop and preserve the necessary expertise in the disposal project for a century [Elk & El, 2011]. Moreover, decisions and actions taken throughout the sequential steps in radioactive waste management are closely interrelated. Accordingly, the technologies used today for collection and the EU Waste Directive need to take account of the characteristics of the future GDF in order to ensure the wastes will be acceptable for disposal in the facility when it is implemented. A national radioactive waste disposal programme involves a number of different actors in the country and the roles and responsibilities of each must be clear. Responsibility starts with the generators of the waste. In the Netherlands, the current policy is that the generator of a single waste stream is in charge of the waste organisation, COVRA, which collects, treats, conditions and then stores the radioactive waste. The eventual implementation of a GDF and therefore also the coordination of research on geological disposal are also tasks of COVRA. A key role is played by the official nuclear regulator appointed by the government. In the Netherlands, this is ANV, which is responsible for assessing the safety of nuclear installations and licensing any activities that these carry out. The public also plays a decisive role and potentially affected communities, in particular, need to be involved in the decision-making process leading to implementation of the GDF. The feasibility of the concept referred to above is less broad within the general public than it is within the technical community, there has been significant public opposition to disposal projects in many countries, including the Netherlands. The repository implementation must therefore take steps to inform and communicate with members of the public in general and with potential host communities for a repository in particular.

After 7 years, OPERA, has reached the stage at which the results can be presented to the public as input for a wider discussion on future progress. Information on the OPERA work is presented in the present report and numerous, more detailed reports have been produced and listed on COVRA’s website. The main thrust of this report, however, is to provide an overview of the arguments and evidence that can lead to enhanced technical and public confidence in the achievable safety levels of a GDF of the design proposed for implementation at depth in the Boom Clay of the Netherlands. This is done by structuring the document in the form of a Safety Case, as is recommended by international bodies and has been done to date in numerous national geological disposal programmes (NEA 2017).

The remainder of the present Chapter introduces the reader to the radioactive waste management organisation in a GDF disposal option lays out concisely the structure of the overarching OPERA research project which has provided much of the detailed input for the Dutch Safety Case. A final section then outlines the structure of the rest of the report which focuses on the specifics of the Safety Case.

### 1.3 Roles of a Safety Case in Geological Disposal

- **‘Safety Case’ is a common term applied in many industries where potential hazards to workers and the public must be assessed.**
The OPERA Research Plan [Verhoef 2011a] expands upon the parliamentary response to the proposed disposal concepts. The proposed designs for a GDF, the operations for emplacement development of the disposal concept for different types of waste, and societal aspects. The main objective of the OPERA research programme is to provide tools and data for the development of safety cases and to organise projects to allow increase technical, public and political confidence.

To address all aspects of these main questions, a multidisciplinary approach covering many areas of expertise is necessary. The tasks in the OPERA research programme are organized in a work package structure, reflecting the different fields of work or disciplines. The programme is organized in a modular way, containing a larger number of separate tasks with well-defined content and clear interfaces with other tasks. This is designed to enable OPERA and future research programmes to evaluate, refine or replace contributions on a very detailed level. The list of tasks initiated in OPERA is illustrated in Figure 1.1 and summarised below. The full list research tasks in OPERA and the resulting reports are described more completely in Appendix 1.

As is noted above and described in more detail in Chapter 3, Safety Cases are produced throughout the long process of repository development. The present Safety Case is far removed from the key safety case for licensing that will be produced only after all issues concerning system design and also facility string have been resolved. The Safety Case at present is a conditional Safety Case, which will however make clear exactly what data are to be directly collected in the future. The Safety Case put forward here is also embedded in the academic course Chemistry of Nuclear Fuel Cycle at Delft University of Technology.

The development of scientific and technical understanding, data and arguments that support the Safety Case for the assessment of the given GDF concept can be structured by addressing specific research questions. In OPERA, six main research topics were selected, related to specific processes determining the safety of disposal in the Boom Clay:

- Future evolution of the geosphere (isolation)
- Integrity of the container/engineered barriers system (EBS) when some of the disposed wastes are generating significant heat (physical containment)
- Source term determining how radionuclides are released from the HLW/LW/LW waste matrices and the engineered barrier system (physical and chemical containment)
- Radionuclide migration in the Boom Clay (transport and retention)
- Radionuclide migration in surrounding rock formations (dilution and dispersion)
- Radionuclide migration and uptake in the biosphere (dilution and dispersion, bioaccumulation).

The programme was run in close cooperation with the Belgian research programme on radioactive waste disposal. Both countries, the host rock considered and many elements of the GDF design are similar. The role of OPERA has been to take all relevant existing knowledge on clay disposal into consideration and then to organise projects to allow development and analysis of a GDF concept specifically for the Boom Clay in the Netherlands.

WORK PACKAGE 4

- Define the goals of OPERA, and the context of a Safety Case for a Dutch GDF

WORK PACKAGE 5

- Characterise clay geological and hydrogeological settings and their evolution

WORK PACKAGE 6

- Develop future scenarios, classify the list of radionuclides for each

WORK PACKAGE 7

- Run assessment models estimating potential consequences of releases from the GDF

WORK PACKAGE 8

- Develop GDF designs, confirm feasibility, study optimisation

WORK PACKAGE 9

- Establish the best trade-off between geological and technical repository characteristics

WORK PACKAGE 10

- Document and discuss results, identify open issues and future work required

WORK PACKAGE 11

- Peer review of Safety Case; assess current state of knowledge (salt and clay)

WORK PACKAGE 12

- Develop GDF designs, confirm feasibility, study optimisation

WORK PACKAGE 13

- Establish the best trade-off between geological and technical repository characteristics

WORK PACKAGE 14

- Document and discuss results, identify open issues and future work required

WORK PACKAGE 15

- Peer review of Safety Case; assess current state of knowledge (salt and clay)

Figure 1.1: Organogram of OPERA and organisation of research in different work packages.
disposal in the Netherlands, the structure of the safety case and the different requirements for geological disposal. The core research programme of OPERA is introduced in Chapter 4. It describes the amount of waste expected to be disposed with the current nuclear programme, the disposal concept investigated in OPERA and the scenarios that are taken into account when calculating the evolution of the GDF and its potential impact on safety. The characteristics of the different components of the GDF, the host rock and the surrounding geological formations are described in Chapters 5 and 6. For each component, the uncertainties that are associated with lack of knowledge and understanding that are relevant for safety are described. Chapter 7 compares the expected and assumed evolution of the system over the next million years. The impact of external factors, such as natural events and future human actions is described. A central part of the safety case is the safety assessment in which potential future doses or risks are evaluated. Chapter 8 shows the results of the calculational modelling. Chapter 9 discusses whether the expected long-term safety of the modelled GDF justifies proceeding to further stages in the geological disposal programme of the Netherlands and Chapter 10 gives a justification for the prioritization of future research. References are listed in Chapter 11. A series of Appendices gives more detailed information on some of the topics introduced at a broader level in the main text.

This chapter aims to give the less directly involved reader a general overview of the concept of deep geological disposal, covering the objectives, the safety measures adopted in a GDF and the practical activities to be carried out throughout the long period from planning through to final closure which might take place only 100 years later.

The concept of using ‘geological disposal’ to manage radioactive wastes originated in the late 1950s, when it was advocated by a panel of scientists and engineers in the USA as the most appropriate way to deal permanently with long-lived, solid radioactive wastes (NRC, 1957). A general technical review of geological disposal was produced by Chapman and Hooper (2012) and this section is based upon the concepts summarised there.

Geological disposal aims to remove a hazardous material from the immediate human and dynamic, natural surface environment to a stable geological environment deep underground where it will be protected from disturbance by disruptive natural or human processes. The wastes and their packaging and containment materials will degrade slowly and even the most stable geological environments will eventually change with the passage of geological time, so that complete containment of all radionuclides for all times is not feasible. However, the radioactivity of the wastes also decreases with time, by natural radioactive decay, and the engineered and geological barriers in the system delay any migration through to the human environment, thus allowing further decay as well as dilution and dispersion. The long-term safety of a geological disposal facility (GDF) therefore depends on the balance of the rates of the processes of radionuclide release, transport and decay.

The basis of geological disposal has been firmly established internationally for the last 30 years on the concept of the so-called ‘multi-barrier system’, whereby a series of engineered and natural barriers act in concert to isolate the wastes and contain them.
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 multi-barrier system can function in different ways at different times in different disposal concepts. Typical, generic components in a multi-barrier system are shown in Figure 2-1, which distinguishes between the engineered barrier system (EBS) and the surrounding natural barrier. An important aspect of the concept is that the barriers should not all lose their functions through a common cause so that the overall functioning of the safety system should compensate for the consequences of breakdown of any one barrier by the protective action of the others [ONDRAF/NIRAS, 2001a: p.17-18].

In OPERA, six components of the overall GDF system are distinguished and are shown in Figure 2-2. The three, inner EBS components lie within the ‘near-field’ of the disposal system, while the natural barrier, comprised of the host rock and the surrounding rock formations, constitutes the ‘geosphere’ or ‘far-field’.

### 2.1 Disposal objectives

The multi-barrier concept of disposal addresses two principal objectives with respect to providing safety (AAEA, 2011a) – isolation of the wastes and containment of the radionuclides associated with them:

- **ISOLATION**: removes the wastes safely from direct interaction with people and the environment. In order to achieve this, locations and geological environments must be identified for a disposal facility that are deep, inaccessible and stable over long periods (for example, where rapid uplift, erosion and exposure of the waste will not occur) and which are unlikely to be drilled into or excavated in a search for natural resources in the future.

- **CONTAINMENT**: means containing the radionuclides within the multibarrier system until natural processes of radioactive decay have reduced the potential hazard considerably – for many radionuclides, a GDF can provide total containment until they decay to insignificant levels of radioactivity within the waste packages. However, the engineered barriers in a disposal facility will degrade progressively over hundreds and thousands of years and lose their ability to provide complete containment. Because some radionuclides decay extremely slowly and/or are mobile in water, their complete containment is not possible in groundwater bearing formations. Assessing the safety of geological disposal involves evaluating the transport and potential impacts of these radionuclides, if they eventually reach people and the surface environment even in extremely low concentrations and at thousands of years into the future.

Fulfilling both of these key objectives is of particular importance during the early years when the hazard potential of the wastes is highest. In fact, because the wastes in the Dutch inventory will have been safely in storage for many decades before they are emplaced in a GDF, their hazard potential at disposal will already have diminished significantly.

Each of the barriers in the multi-barrier system contributes to ensuring isolation and containment. A genetic set of such contributions to safety is shown in Table 2-1.

### 2.2 Isolation

- **Component High-Level Waste Lower- and Intermediate-Level Waste**

<table>
<thead>
<tr>
<th>Component</th>
<th>High-Level Waste</th>
<th>Lower- and Intermediate-Level Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastes</td>
<td>Suitable for isolation</td>
<td>Suitable for isolation</td>
</tr>
<tr>
<td>Source</td>
<td>Suitable for isolation</td>
<td>Suitable for isolation</td>
</tr>
<tr>
<td>Migration</td>
<td>Suitable for isolation</td>
<td>Suitable for isolation</td>
</tr>
<tr>
<td>Leaching</td>
<td>Suitable for isolation</td>
<td>Suitable for isolation</td>
</tr>
<tr>
<td>Transport</td>
<td>Suitable for isolation</td>
<td>Suitable for isolation</td>
</tr>
<tr>
<td>Sorption</td>
<td>Suitable for isolation</td>
<td>Suitable for isolation</td>
</tr>
<tr>
<td>Radiation</td>
<td>Suitable for isolation</td>
<td>Suitable for isolation</td>
</tr>
</tbody>
</table>

### Barrier component

<table>
<thead>
<tr>
<th>Wastefrom: the solid waste material</th>
<th>Generic contributions to Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provide a stable, low-solubility matrix that limits the rate of release of the majority of radionuclides by dissolving slowly in groundwaters that come into contact with it</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2-1: Post-closure contributions to safety of the principal barriers in the multibarrier systems (adapted from Chapman and Hooper, 2012)
Box 2-1 discusses the declining radioactivity of wastes as a function of time, from which it can be seen that this reduces by factors of many thousands to hundreds to a few thousand years, depending upon the waste type. Providing safe isolation and containment over this ‘early’ period of the highest hazard potential is perhaps the most important objective of a GDF.

An essential aspect of geological disposal is that a GDF provides protection and safety in a completely passive manner once it has been closed – no further actions are required from people to manage the facility. These wastes, and, over immensely long times, the facility and the wastes become part of the deep, natural environment.

It is expected that the operational life of a typical GDF would be many decades, even over 100 years in some countries, depending on how much ‘backlog’ waste exists and how much is to be produced in the future, after the repository becomes available. In all cases, the intention is that, upon closure of the operation of the GDF will be backfilled and the access works will be completely sealed. After it has been closed, conditions in the rocks surrounding the repository at depth will return slowly to those of the natural, undisturbed environment before the GDF was constructed.

2.2 Different options for the geological host rock

Over the last 40 years, geological disposal has developed from a concept to reality, with the world’s first GDF for spent fuel currently under construction (at Olkiluoto in Finland, for spent fuel disposal). Over the last 40 years, a range of generic, but host rock-specific, studies have been carried out (Hart et al., 2015a and 2015b) and many of the research tasks carried out in OPERA are also relevant for a salt repository [e.g. inventory, overburden characteristics, safety assessment methodologies]. However, OPERA is principally focussed on clay formations, with the Boom Clay being the primary host rock considered and the one used to develop the OPERA safe case (see Chapter 5).

2.3 Activities through the lifecycle of a GDF

The major activities through the lifecycle of a GDF (Figure 2-3) are site selection, GDF construction, operation and closure. There is relevant international experience on each of these stages, except for closure. At present, one purpose-built GDF is fully operational (the WIPP repository in the USA for defence wastes) and one is under construction (at Olkiluoto, for spent fuel disposal). There are numerous examples worldwide of GDF site selection programmes, although only a few of these have so far continued successfully through to licensing and acceptance. This section looks at the potential Dutch approach to each stage and, where possible, at an international example.

2.3.1 Site selection

Finding a suitable location for the Dutch GDF is an activity that lies decades into the future. OPERA has not addressed how this project will be designed and implemented, but it is important, even at this early stage, to have confidence that an appropriate approach to siting can be developed and a solution found. A siting selection process has not been established in the Dutch policy but in order to have a visualisation of this process, lessons-learned from foreign countries are described here.

Many national geological disposal programmes have suffered setbacks and delays because their GDF siting projects have proved difficult or impossible to implement. In general, this is because it has proved hard for implementers to prepare and present the appropriate mix of technical, societal and political inputs that is required to achieve consensus amongst the stakeholders. However, the success of several national programmes recently is indicative that this problem can be overcome, largely by recognizing that siting needs to be an open and inclusive process for all parties concerned.

Figure 2-3: Stages in the lifecycle of a geological disposal facility (GDF).

Getting technical information to help identify suitable regions and, eventually, specific locations, involves iterative programmes of data evaluation and eventual site investigation to characterise the geological environment in great detail. At each stage information is generated in progressively more detail, for the design of the GDF and for the system modelling that is central to long-term safety assessment. Generally, GDF design and safety evaluation will go through several stages of development, as more and more specific information becomes available. The basic geological and geo-technical characteristics of the host rock and surrounding formations must be adequately understood and, for the safety case, an integrated picture must be built up of the dynamic evolution of the deep environment during tens of thousands to a few million years.

This requires the compilation and interpretation of observations made by many field, laboratory and remote sensing techniques, at a wide range of spatial scales. This will rely on use of data available from other geotechnical, survey and exploration activities in the Netherlands, plus dedicated deep drilling, testing and sampling in boreholes. Identifying, scoping and managing technical uncertainties will be a key activity within the siting programme.

Also in the Netherlands, a gradual multi-step GDF development process (frequently referred to as ‘staging’) is possible. The principles of an approach have been described in overview documents such as “One Step at a Time”, produced by the National Research Council of the US National Academies [NRC 2003] and “Stepwise Approach to Decision Making for Long-term Radioactive Waste Management” (Guiding Principles) produced by the OECD Nuclear Energy Agency [NEA 2004b].

One challenge is to develop a suitable process for ensuring that all stakeholders are involved in decisions at the appropriate times, especially national and local governments, regulators and local communities. International experience with siting waste facilities has shown that an essentially prescriptive approach (where technical choices are made by experts and then attempted to be convinced specific communities) is often unworkable. The opposite end of the ‘siting spectrum’ is pure volunteering, in which an interested community can come forward, explore the issues and, if wishes, be evaluated for suitability, with the implementer prepared to show technical flexibility, provided a safe and economic solution can be developed. In the pure volunteer model, the implementer does not seek sites, but waits for volunteers to propose potential areas or sites whose suitability will be objectively assessed. An intermediate approach is for the implementer to establish any clear exclusion criteria that would automatically rule out areas of unacceptable unsuitability and then to seek volunteers in any of the non-excluded regions. This approach is currently being developed in the UK and Japan, for instance.

For the Dutch GDF, siting strategy needs to be established in national policy. COVRA assumes that the siting strategy will also be based on a volunteer model incorporating stakeholder involvement at all stages. It would be technically guided at the outset only insofar as clearly unsuitable regions were excluded at the start. For example, a relevant geological criterion could be that candidate sites should have a formation to host the waste that shows no evidence of potential chemical erosion because there is evidence that this potential event could impact on the post-closure safety. It is considered important today that the eventual strategy should incorporate the flexibility to evaluate objectively any proposals that might emerge from volunteer communities or regions, from the start of the programme.

2.3.2 Construction

As observed above, experience in the construction of GDFs is limited. The Waste Isolation Pilot Plant in the USA is an operational geological disposal facility. Construction in Finland has extended to approximately 6500 m underground. Construction experience in other rock types has been gained through the excavation of underground rock laboratories (URLs). In Finland, the underground rock characterisation work for the EURAMET ONKALO project was undertaken at approximately 450 m depth. The URLs are excavations extending to a depth of about 450 m. ONKALO was built such that the important characteristics of the host rock for
Figure 2-4: A large TBM (7.1 m diameter) used for the boring and lining of 4.2 km of 6.2 m diameter rail tunnels for the Crossrail system at depths of up to 40 m beneath London. The image shows how concrete tunnel liner segments are emplaced behind the cutting head as tunneling progresses, as envisaged for the Dutch GDF tunnels (image: crossrail.co.uk).

In summary, there is considerable experience in civil and mining methods during construction were drilling and blasting, with sections of the shafts being constructed by raise boring. ONKALO forms the access system and central service area for the panels of disposal tunnels, on which construction work began in December 2016.

In a deep clay formation, it is most likely that tunnel-boring machines would be used for much of the GDF excavation, especially the disposal tunnels. In poorly indurated clay such as the Boom Clay, a thick concrete tunnel liner system is required to provide support against convergence of the clay during construction and operation. The tunnel-boring machines used for construction and lining of galleries in the Belgian underground research laboratory (URL) at Mol is similar to the machine used for the construction of traffic tunnels in the Netherlands, for example in Boom Clay at the Westerschelde tunnel, although the diameter of (shallow) traffic tunnels is considerably larger than was used at the underground research laboratory or would be feasible in a deep GDF. Figure 2-4 illustrates a large TBM (7.1 m diameter) recently used in the construction of the Crossrail system beneath London.

In France, an extensive URL (Figure 2-5) has been operating in a clay formation since 2005, with studies on appropriate construction methods being part of ANDRA’s work. The Jurassic clay formation proposed for the French GDF is more indurated than the Boom Clay and ANDRA currently favours the use of conventional tunnelling techniques. The French URL example is shown here to indicate that the underground excavations associated with a GDF can be relatively complex, and are likely to include not only disposal areas, but pilot facilities, experimental and demonstration areas, tunnels for machinery storage and maintenance, laboratories, offices etc. In summary, there is considerable experience in civil and mining engineering that can be applied when constructing a deep GDF. Specific challenges for disposal facilities are the minimization of disturbances to the host rock and the understanding of its long-term behaviour. Construction activities must be managed so that they do not adversely affect the hydrogeological and geochemical properties of the various system components that are important safety features of the repository system.

Figure 2-5: The extensive excavations that form the French URL at 480 m depth in clay at Bure, in northeast France (source: ANDRA). Note that the more indurated (stronger) host clay formation permits the use of tunnel junction designs that would not be possible in the lower strength Boom Clay.

2.3.3 Operation

Some radioactive wastes have been disposed deep underground in the past, e.g. at the Morsleben and Asse facilities in Germany, but these made use of existing mines, not staked or designed using present criteria for a GDF. The only operating, purpose-constructed GDF at present is the WIPP facility mentioned above (Figure 2-6) which has been in operation since 1999.

Figure 2-6: The WIPP facility in bedded salt formation in New Mexico, USA, for the disposal of defence transuranic and other wastes. This cavern has been excavated in the salt using conventional mining techniques.

The first operational disposal facility for spent fuel will be in Finland (Olkiluoto), where a construction license has been issued and it is planned to submit an application for an operating license in 2020. Sweden is currently going through the steps of evaluating a construction license application for its spent fuel GDF at Forsmark and it is also expected that France will reach an operational stage in its GDF in clay in about 2025, with a construction license application being submitted in 2017. There is considerable experience with operation of licensed repositories for low-level radioactive waste. Some 30 countries currently operate LLW-repositories, some of them in caverns and tunnels at depths of tens of metres beneath the surface.

Operational safety will be based upon conventional underground civil engineering and mining practices, plus mature nuclear safety approaches and technologies from operating nuclear facilities worldwide. Much of the nuclear-specific know-how is directly transferable from existing nuclear installations (e.g. for zoning of radiation protection and remote and active handling of materials), although new approaches will be required to address novel features of GDF design and waste package handling underground.

Eventually, as the Dutch GDF design develops, it will be necessary to begin assessments of the factors affecting operational safety, both conventional and radiological. These types of assessment have been carried out already in the more advanced national GDF programmes and elements of them form part of the environmental safety cases developed for licensing purposes. This type of work does not form part of the current OPERA programme.

2.3.4 Closure and beyond

The Dutch GDF will not be closed until well into the 2100s and the process will thus make use of approaches and technologies available in the distant future. Nevertheless, it is important today to be able to show that the GDF can be closed and sealed safely, using existing technologies. A key issue will be the sealing of disposal tunnels and panels, and most focus has been in this area. Even though closure of disposal tunnels is some time into the future in other EU national disposal programmes, there has already been extensive, full-scale development and testing of plug designs and emplacement methods. Figure 2-7 shows the DOMPLU disposal tunnel plugging test, performed in Sweden.

In addition, backfilling and seal emplacement in shafts and inclines will require the use of a variety of materials and techniques. There has been considerable work in URLs worldwide on tunnel backfilling and seal design and emplacement methods, at full scale, in different geological environments. These trials have shown that adequate sealing can be achieved of sections of a GDF during the operational period and also of the whole system at final closure.

As the first operating GDFs are only just starting, there are, of course, no examples of final closure at present. However, there are analogous demonstrated examples of closure of deep underground chemical waste disposal facilities in rock salt at 500 metres depth in Germany (NEA,2013c).

The post-closure period covers all times after the closure and effective decommissioning of the GDF, including removal of the surface works and any remediation of the site that is required. In the far future, decisions will need to be taken by future generations on when to terminate any activities or systems that have been put in place to facilitate waste retrievability during operations.

Figure 2-7: The cast concrete face of the composite DOMPLU test disposal tunnel plug at the Äspö URL in Sweden (image: SKB).
Box 2-1: Addressing the long timescales in the OPERA Safety Case

Unlike the approach of society to practically all other potentially hazardous materials that find their way into the environment, there is a commitment among those managing radioactive wastes to ensure safety at all times to levels at least as protective as those provided today. This has meant looking farther into the future than has been attempted for any engineering project – not just a few generations (the design life of most engineered structures), but many tens of thousands of years. Typical GDF safety assessments consider potential impacts on future generations out to a million years – a timescale that is hard to imagine for most people. However, even such an immense time period is relatively short for a geologist, used to considering how our natural environment has evolved over hundreds of millions of years.

Of course, forecasting the future behaviour of a GDF for such long times brings with it increasing uncertainty as we look farther into the future. The level of uncertainty depends on the particular geological environment being studied, the materials used in the GDF and the physical and chemical processes being evaluated. For some materials or processes, we can only be confident in our predictions of behaviour for thousands of years. For others, particularly many geological processes, we can have confidence in our predictions for hundreds of thousands or even millions of years.

Furthermore, radioactive wastes possess one quality that sets them apart from many other hazardous materials and that puts the issue of the long timescales in a different perspective: owing to the natural process of radioactive decay, their radioactivity reduces with time. If the GDF system prevents radionuclides returning to the human biosphere for sufficiently long, they will no longer present pose risks for humans. The rate and scale of reduction in radioactivity depends on the radionuclides contained in the wastes. Because much of the original activity in the most radioactive categories of COVRA’s waste is present as radionuclides that decay relatively quickly (e.g. Sr-90 and Cs-137, whose activity halves every 30 years), most of the activity disappears within the first thousand years. This early decay in radioactivity reduces to some extent concerns about the long timescales that are being considered. However, the potential impacts of longer-lived radionuclides must clearly also be taken into account – and this is a central aspect of the OPERA safety assessment in Chapter 8. It is important, therefore, to consider in more detail how the total radioactivity of the wastes changes with time.

In practice, when considering the potential impacts of radionuclides on humans, it is their ‘radioxicity’ rather than their radioactivity that is more relevant. This is a measure of the radiation doses that would result if all the radionuclides in a given amount of waste were to be dissolved in water, which was then drunk by people. This is entirely hypothetical, but it does allow comparison of how hazardous different types of radioactive materials can be. For example, it allows comparisons between the radioxicity of spent fuel or HLW and the radiotoxicity of the natural uranium ore from which the fuel was produced. An example of the calculation of relative radioxicity of wastes is shown in the figure below.

The figure plots the declining radioxicity of spent fuel and HLW as a function of time after the fuel has been taken out of the reactor or, for HLW, after it was manufactured, following the reprocessing of the equivalent quantity of spent fuel. These curves are shown normalised to the radioxicity of the amount of uranium ore that was originally used to make the fuel (the horizontal line). It can be seen that, when fuel comes out of a nuclear reactor, it is many thousands of times more radioxic than the uranium ore from which it was manufactured, but this diminishes significantly over a period of a some hundred years. The ‘crossover’ time, when spent fuel has a similar level of radioxicity to the original ore, is in the order of a hundred thousand years. HLW has an equivalent ‘crossover’ time of only about 3000 years.

By this time, the large reduction in hazard potential that has occurred means that the primary functions of geological disposal have, largely, been achieved by isolating and containing the waste until it presents a similar hazard potential to materials found in nature and, specifically, those from which it was originally manufactured. Of course, it must also be acknowledged that uranium ores themselves can present hazards and that the wastes are now in a different location from the original ores. Accordingly, the safety case still needs to consider the possible impacts on people and the environment of the residual radionuclides that do not decay for very long times. These are predominantly radioisotopes of the heavy elements such as uranium, neptunium and plutonium and of fission products such as 135Cs and 137Cs. However the former group are strongly retarded in the GDF and the latter although mobile in groundwater have low radiotoxicities.

What this illustrates for the design and safety assessment of a GDF is that considerable care clearly needs to be taken that complete isolation and containment are achieved over the first hundreds of years after closure. In the early period after closure, it is appropriate to judge possible health impacts on people using normal radiological protection standards. In the longer term, the hazard potential is much less, and in the very long-term we are dealing with something similar to naturally radioactive materials. Consequently, as the timescale increases beyond a few thousand years and out to a million years, it becomes more appropriate to assess hazards using other measures, more related to our daily exposure to natural radioactivity. These are discussed in Chapter 8.
3. Approach to demonstrating repository safety

As explained in Chapter 1, demonstration of the safety of a GDF is achieved through the preparation of a series of safety cases carried out sequentially, at key phases of programme development. The present Chapter explains in more detail the safety strategy, the structure of the initial safety case prepared by COIRRA and the roles the Safety Case will play throughout all phases in GDF implementation. The principal safety impacts of the GDF are measured in terms of radiation doses that might be received by members of the public. Therefore the following section describes the allowable dose targets or limits that have been laid down in regulations. These issues are discussed at length in report OPERA-NRG 1222 [Hart, 2017].

3.1 Required levels of safety

Clearly, in order to judge whether a safety case has demonstrated convincingly that a GDF will give rise to no unacceptable impacts on people, agreed limits for such impacts should be established. Calculating the potential consequences of releases of radionuclides from a GDF is, in principle, a purely technical challenge. Judging whether the calculated releases would be acceptable to people is, in principle, a purely technical challenge. Whether the calculated releases would be acceptable to people is, in principle, a purely technical challenge. 

The EU radiation protection criteria and standards are derived from the recommendations made by ICRP, in particular those made in 2007 in ICRP Publication 103 (which sets down a limit of 1 mSv/yr for the total dose to any member of the public from any regulated source) and in 2013 in Publication 132 (which proposes a lower constraint of 0.3 mSv/yr per year for a GDF). In Article 6 of the Dutch Radiation Protection Decree of 2001 the total individual radiation dose allowed for members of the public is fixed at 1 mSv/yr (with any single source being limited to one tenth of this, i.e. to 0.1 mSv/yr). Although no specific limits have yet been set in the Netherlands for potential releases from a GDF, taking the above guidance into account and also examining regulations in various countries suggests that a dose limit of 0.1 to 0.3 mSv/yr is a sensible guideline when assessing whether required safety levels are achieved. To give some perspective on these numbers, it can be noted that the average total radiation exposure to individuals in the Netherlands is about ten times higher, namely 2.6 mSv/yr - with around 61% of this coming from natural sources and 38% from medical treatments [RIVM, 2013] as shown in Figure 3.1.

Average exposure in the Netherlands

The uranium and thoron series (with a dose of 0.11 mSv/yr per year) [UNSCEAR, 2000, p.140]. Specific Dutch data to calculate natural exposures are available: effective dose rates of the thorium and uranium daughters by ingestion of food and drinking water are 7, 4, 15 and 36 µSv per year for Ra-228, Ra-226, Pb-210 and Po-210 [Bourguiden, 2016].

3.2 Structure of a safety case

Expanding upon the concise definition of a Safety Case as given in Chapter 1, the IAEA/NEA gives guidance notes that include the following key points: The safety case has to:

- provide the basis for understanding the disposal system and how it will behave over time
- address site aspects and engineering aspects, providing the logic and rationale for the design, and has to be supported by safety assessment
- identify and acknowledge the unresolved uncertainties that exist at that stage and their safety significance, and approaches for their management
- include the output of the safety assessment together with additional information, including supporting evidence and reasoning on the robustness and reliability
- and may also include more general arguments and information to put the results of safety assessment into perspective.

The components of the safety case as defined by the IAEA [2012] are portrayed graphically in Figure 3-2.

In the present report, each of these items is addressed at some point. The context of the safety case has been mentioned already in Chapter 1; increasing confidence, enhancing knowledge and planning future R&D. The following section 3.3 gives more details on the overall safety strategy. A high-level system description for GDFs in three different host rocks is covered in Chapter 2. For a GDF in Boom Clay, the system description is covered in Chapters 4, 5 and 6. Chapters 5 and 6 also discuss how the system components contribute to safety. In a safety assessment, when assumptions need to be made, these are chosen to be conservative, i.e. pessimistic; however, a best estimate of the expected evolution can also be made and this provides an understanding of how pessimistic the assessment assumptions are. Chapter 7 shows the realistically expected and the conservatively assumed evolution for the safety assessment. Chapter 8 gives the numerical results of safety assessment calculations; Chapter 9 integrates all of the previous work to formulate conclusions. Discussion of uncertainties has not been allocated a specific section; instead the uncertainties associated with each of the important processes described or with the data employed are addressed at the appropriate section. In addition the final Chapter summarises uncertainties and open questions. Design iterations as indicated in the IAEA structure have not yet been performed, but indications are given in Chapter 4 and 6.

Figure 3-2: Components of a Safety Case (IAEA 2012)
### 3.2.1 The safety strategy

According to both IAEA and NEA guidance documents, one of the initial components of the safety case should be a safety strategy ([IAEA, 2012; NEA, 2013a]), which is defined as a high-level approach for achieving and maintaining safety of radioactive waste. The implementer (i.e., COVRA) should develop the safety strategy. In the current phase of work in the Netherlands, the strategy should provide for a systematic process for developing, testing and documenting the present level of understanding of the performance of a GDF and for building and maintaining the necessary knowledge and competences through successive research programmes. It is important to note that the safety strategy is a living document; it, and also the disposal concepts based on the strategy, will develop iteratively over the whole implementation period, which in the Netherlands is planned to last about 100 years.

The safety strategy also includes the definition of the national and international requirements to be satisfied and the selection of the strategic requirements made by the programme implementer to accomplish this. National and international requirements are derived from relevant national and international regulatory frameworks (IAEA, EU, ICRP). COVRA’s strategic requirements are high-level preferences based on existing knowledge and understanding. Both are used to define further requirements to be satisfied. In OPERA, the safety strategy has been chosen to focus on the on-going research work by developing a hierarchical set of different levels of requirements in a requirements management system, as shown in Figure 3-3.

#### 3.3 Roles of the safety case

The Netherlands is committed to a step-wise, adaptive staging approach to siting, designing and constructing the GDF. At various stages in the GDF development programme, decisions are needed to proceed through the lifecycle and move towards the next stage; these decisions should be supported by a series of safety cases.

The iterative nature of the safety case is apparent when one considers Figure 3-3. This shows the common steps or stages in the decision-making processes leading to geological disposal and indicates the key stakeholders involved, as well as the planned timing for the Netherlands, as laid down in current Dutch policy.

At each decision point, the safety case has to provide the safety-related information that allows a judgment on whether to proceed to the next stage.

The nature of the decision and the characteristics of the safety case for each of the stages in repository development are commented upon below, based on two IAEA documents ([IAEA, 2011b: p25–26; IAEA, 2011c: p45–46]).

<table>
<thead>
<tr>
<th>Level</th>
<th>National and international requirements</th>
<th>Description</th>
<th>COVRA’s strategic requirements</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td></td>
<td>General requirements set out by govern-ment, EU and IAEA</td>
<td></td>
<td>The policy in the Netherlands is that all hazardous and radioactive waste must be isolated, controlled and monitored.</td>
</tr>
<tr>
<td>Level 2</td>
<td></td>
<td>Strategic choices: requirements from IAEA policy and long-term strategy</td>
<td>COVRA must provide continuous care for radioactive waste in the Netherlands during the period of long-term interim storage that precedes disposal and must advance Dutch knowledge about geological disposal by doing research.</td>
<td></td>
</tr>
<tr>
<td>Level 3</td>
<td>Strategic requirements for the GDF</td>
<td>High-level requirements for the GDF safety and operational functions</td>
<td>Safety is provided by multiple safety functions. A safety function is the action or role that a natural and/or engineered barrier performs after closure of the GDF to prevent radionuclides in the waste from posing an unacceptable hazard to people or the environment.</td>
<td></td>
</tr>
</tbody>
</table>

#### 3.3.1 Need for action

When a country starts generating radioactive waste, there is a need for action by the government, which has to define a policy to meet this responsibility by managing the different steps, from collection to eventual disposal. Commonly, the government nominates or establishes an organisation responsible for implementing disposal. The Netherlands has already passed this stage, with COVRA being the nominated agency to manage Dutch radioactive wastes.

#### 3.3.2 Disposal concept

The government lays out the boundary conditions for geological disposal. In the conceptualisation phase, during which disposal concepts and potential host rocks are considered, the implementer establishes the safety strategy using the boundary conditions and carries out preliminary safety assessments for post-closure. Regulatory review of the work at this stage should guide the implementation programme on the likelihood of achieving the necessary demonstration of safety. This is effectively the current stage of the OPERA programme.

#### 3.3.3 Site selection

The government, together with the GDF implementer, must develop a national framework for decision-making on site selection. For successful projects, this must be widely supported, and adhered to, by the relevant actors. The national framework should support participation, flexible and accountable decision-making processes. For example, the implementer identifies potentially suitable sites that are compatible with the disposal concept(s) and characterises these sites to the extent that a decision can be made on a preferred site. In the Netherlands, it is not yet decided who will identify potentially suitable sites but in any case, a key element of the basis for this decision should be a safety case, including at least an outline of the operational safety case together with a comprehensive post-closure safety case.

Local and regional stakeholders are included in Figure 3-4 because they have an important role during the lifecycle of GDF, especially during the establishment of a site selection process and onwards. Public information, consultation and/or participation in environmental and operational planning are today’s best practice and must take place at the relevant different geographical and political scales. Large-scale technology projects are more likely to be accepted when local and regional stakeholders have been involved in making them possible and have developed a sense of interest in, or responsibility for, their success. For the Netherlands, the stage of site selection lies far in the future, probably not beginning until the second half of the 21st Century. However, the approaches to be used and the decision processes that will be applied must be proposed, discussed by all stakeholders and agreed at an earlier phase in the disposal programme.

#### 3.3.4 Construction

The disposal concept chosen is adapted to the (measured) site conditions. The safety concept developed in this phase is the basis of the implementer’s application to construct the facility. The basis for the decision of the regulator to grant a licence to the implementer to construct the facility is the submitted interim operational and the post-closure safety case.

#### 3.3.5 Operation

The implementer must have demonstrated that it has built the facility in accordance with the terms of the construction licence in advance of the decision to proceed to the operational phase. Considering the limited amount of Dutch waste to be disposed, all disposal galleries will likely be built before waste is received to be emplaced. The basis for the decision of the regulator to grant a licence to the implementer to receive waste in the facility, emplace waste, backfill and seal the galleries are the submitted final operational and advanced post-closure safety case.

#### 3.3.6 Operational upgrade

During operation, the implementer provides periodic updates of the operational and post-closure safety cases. These updates can take into account interpretation of data obtained by, e.g., monitoring the emplaced waste in a pilot facility or on-going surface monitoring programmes. These results will be periodically reviewed (e.g., every 10 years) by the regulator in order to judge whether the system continues to satisfy all safety requirements.

#### 3.3.7 Closure

The final post-closure safety case includes a plan for any post-closure institutional controls, monitoring and surveillance. This plan supports the implementer’s application to close and seal the facility.

#### 3.3.8 Post-closure

The implementer must have demonstrated that it has closed the facility in accordance with the terms of the licence to close the facility. A detailed plan for any proposed institutional controls, continuing monitoring and surveillance will be provided to the regulator. The implementer may need to provide an additional post-closure safety case in which the behaviour of the disposal system is shown to be as predicted. This safety case may support the decision of the regulator to start the -licensing phase.

#### 3.3.9 Post-licensing

Monitoring and surveillance are no longer the responsibility of the implementer; the national government takes over this role and (I)AEA post-licensing requirements (with respect to any fissile materials contained in the GDF) might be satisfied by remote means (e.g., satellite monitoring, aerial photography, micro-seismic surveillance). All relevant information of the location of the GDF is expected to be accessible as obliged by the implementer of the European Directive for the establishment of the Infrastructure for Spatial Information in the European Community ([EU, 2007a:13]). It is likely that it will require national governmental decisions in order to regulate any monitoring, surveillance or safeguarding activities and control or prohibit activities, such as exploration drillings, in the vicinity.

#### 3.4 Requirements Management System

This section illustrates the importance of the requirements at the four levels mentioned in section 3.2.1. The complete list of items in the COVRA requirements management system is relevant for...
In the context of the present Safety Case, the key specific national requirements for geological disposal of radioactive waste in the Netherlands include the following:

- The policy in the Netherlands is that all hazardous and radioactive waste must be isolated, controlled and monitored.

Strategic requirements are introduced by COVRA itself; of particular relevance to the GDF Safety Case are the following:

- COVRA must provide continuous care for radioactive waste in the Netherlands during the period of long-term interim storage that precedes disposal and must advance Dutch knowledge about geological disposal by doing research.
- COVRA prefers simple, robust and proven designs of structures, systems and components to facilitate safe long-term operations.
- The disposal programme should take stock of available international knowledge. COVRA has a research and development agreement with the Belgium waste management organisation DNDRAF/NIRAS which has extensive experience in developing a GDF concept for Boom Clay. COVRA is also involved in numerous international research studies.

Strategic requirements of the implementer (COVRA) for safe emplacement and closure of the GDF can include items based on input received at local and regional information meetings, e.g., during site investigations.

- Safety is provided by multiple safety functions. A safety function is the action or role that a natural and/or engineered barrier performs after closure of the GDF to prevent radionuclides in the waste ever posing an unacceptable hazard to people or the environment.
- The description of multiple safety functions for a facility in clay is described in Chapter 4.
- The depth of the GDF should be sufficient to protect the facility from the effects of geomorphological processes such as erosion and glaciation during ice ages.
- Waste types will be divided into groups to be emplaced in separate sections of the GDF in order to prevent or minimize the influence of the products generated by degradation of waste matrices and pastigages on other types of waste.
- For heat-generating waste, the engineered barriers will be designed to provide complete containment of the wastes at least through the thermal phase.
- The engineered barriers for heat-generating HLW should not be be penetrated with present drilling.

**IAEA Safety Principles**

- Principle 1 Responsibility for safety
- Principle 2 Role of government
- Principle 3 Leadership and management for safety
- Principle 4 Justification of facilities and activities
- Principle 5 Optimization of protection
- Principle 6 Limitation of risks to individuals
- Principle 7 Protection of present and future generations
- Principle 8 Prevention of accidents
- Principle 9 Emergency preparedness and response
- Principle 10 Protective actions to reduce existing or unregulated radiation risks

**Strategic requirements of the implementer (COVRA)**

- Disposal is foreseen after interim storage above ground for a period of at least 100 years.
- Radioactive waste is intended to be disposed of in a single, deep GDF, so that no separate facilities for LILW and HLW are envisaged.
- National radioactive waste management disposal policy requires that any GDF be designed in such a way that each step of the implementation process is reversible.
- Both rock salt and clay formations are considered as potential host rocks for geological disposal in the Netherlands; the present Safety Case focuses on clay.
- The public has to be given the necessary opportunities to participate effectively in the decision-making process regarding radioactive waste. The present report and all accompanying reports are intended to provide the public with necessary information.

Figure 3-4: Key stakeholders and common elements in the decision-making processes on geological disposal of radioactive waste with the planning for the Netherlands.
This Chapter introduces the waste materials that are destined for geological disposal in the Netherlands and the currently proposed design of the geological disposal facility (GDF), which is used as the basis for the OPERA safety case. It goes on to describe how the disposal system is intended to provide the safety functions discussed in Chapter 2 as the GDF evolves as part of the deep geological environment with the passage of time, out into the far future.

4.1 The wastes destined for geological disposal

The inventory of wastes that will eventually be placed in the Netherlands GDF depends on the future utilisation of nuclear energy. The OPERA waste inventory is based on the Dutch base scenario: no new nuclear power plants and operation of the present nuclear power plant until its intended closure in 2033 (Scenario 1a in the Ministry of Economic Affairs, Energierapport 2008).

This waste inventory differs from the total Dutch inventory of radioactive wastes. For example, the largest volume of radioactive waste is that of Naturally Occurring Radioactive Material but only 3.4% of its estimated volume is transferred to COVRA for storage and disposal [Verhoef, 2014a]. In OPERA, only waste destined for geological disposal is considered.

For OPERA, the previous CORA programme waste inventory for safety assessment [Grupa, 2000] was updated to reflect changes in waste generation: the generation rate of some waste has declined over time (e.g. LLW generation from hospitals, industry and research institutes), some increases in wastes are expected due to the extension in operation period (e.g., waste from Borssele nuclear power plant) and new wastes have been taken into consideration (e.g., depleted uranium).

In the Netherlands, radioactive waste is classified into Low and Intermediate Level Waste (LLW), Naturally Occurring Radioactive Materials (NORM), including Technically Enhanced NORM (TENORM), and High Level Waste (HLW). The expected inventory of these wastes that is destined for geological disposal is shown in Table 4-1.

It can be seen that the largest mass and volume when packaged for disposal is LLW, about half of which is TENORM, in the form of depleted uranium. There is less than 300 tonnes of spent fuel and vitrified HLW, before packaging for disposal.

The handling and disposal technologies for these different waste types will depend, not only on their quantities, but also on their levels of total radioactivity and on the radionuclides which contribute to this. These data are given in Chapter 8 of this report.

4.1.1 LLW

Low and intermediate level radioactive waste (LLW) arises from activities with radioactive materials or radionuclides in among others industry, research institutes and hospitals. It includes lightly contaminated materials, such as plastic, metal or glass objects, tissues and cloth. The size of the LLW containers is standardised...
and optimized to ease their handling. Four types of packages with volumes of 200, 600, 1000 or 1500 litre are stored at the COVRA site. The 200 and 600 litre containers consist of painted, galvanised steel drums with an inside a layer of cement, embedding the waste. The 1000 and 1500 litre packages are full concrete packages wherein a cemented waste form is contained. In each package, half of its volume is at least cementitious material. Most of the LILW packages can be handled easily and transferred to a geological disposal facility without significant additional shielding. The LILW is conditioned with concrete and is expected to be suitable for disposal without further packaging or conditioning.

### 4.1.3 HLW

The high level waste consists partly of heat-generating waste (vitrified waste from reprocessed spent fuel from the Nuclear Power Plants in Borssele and Dodeweerd, conditioned spent fuel from the research reactors and spent uranium targets from molybdenum production), and partly non-heat-generating waste such as hulls and ends from fuel assemblies that have been disassembled during reprocessing. Heat generation is a result of the continuing radioactive decay of the radionuclides in the wastes. As time progresses, the heat output decreases due to the ongoing decay. The amount of heat generated depends on the type of waste, its composition and/or the burn-up of the fuel. It is expected that some other non-heat-generating HLW will be generated in future, including waste from dismantling and decommissioning nuclear facilities, or historical wastes not yet stored at COVRA. The amount is presently estimated at about 600 tonnes. For the purpose of the OPERA study, it is assumed that this waste is packaged the same kind of canisters as used for spent fuel from research reactors and conditioned with concrete. HLW is expected to require further packaging and/or conditioning before disposal.

### 4.2 The OPERA geological disposal facility (GDF)

The GDF design used as the basis for OPERA consists of both 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. This depth is considered to provide adequate isolation of the GDF not only from people, but also from the effects of many long-term, dynamic surface phenomena, such as those caused by climate change. The Boom Clay (see Chapter 5) is characterised by its very low permeability to water, meaning that there is no significant flow of groundwater through the formation. Instead, any movement of chemical species towards or away from the GDF will be predominantly by the extremely slow process of diffusion in the pore waters of the clay.

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 – smaller thicknesses might also be feasible. This is in line with previous research in the Netherlands and the Belgian disposal concept [ONDRAF/NIRAS, 2001b: p.15].

#### 4.2.1 Surface facilities

The surface facilities are required for receiving, inspecting and conditioning the different waste types (the Waste Conditioning Facilities: WCF). Surface facilities also include support infrastructure for construction, operation and closure activities in the underground disposal facility (the Construction and Supply facility: C&S). The surface facilities will be split into a (radiological) controlled area where all waste handling will take place and a non-controlled area, mainly involved in the constructional works. OPERA concentrates on the feasibility and long-term safety of geological disposal and is thus concerned only with the underground parts of the GDF, so that no detailed design considerations have yet been given to the surface facilities.

#### 4.2.2 Underground facilities

The underground facilities contain separate disposal sections for the different types of wastes, a pilot facility and a workshop for maintenance work, all connected by a main gallery. The main gallery is an planar structure, which connects with the ground level via two access shafts and/or an (optional) inclined ramp.

The facility contains four waste disposal sections: for vitrified HLW, for spent fuel from research reactors, for non-heat-generating HLW and for the disposal of LILW and depleted uranium (Figure 4-1-2). Each section is optimized with regards to dimensions and modes of transport of the waste containers through the galleries. The proposed dimensions of the shafts and galleries in the OPERA disposal concept are summarized in Table 4-1-1.

In order to guarantee safety in case of accidents such as water ingress during the operational phase and during the period where a possible retrieval of the waste is foreseen, a layout has been selected in which all disposal drifts have a dead-end topology. Even if the repository is flooded and water infiltrates the galleries, no flow circulation can occur through the disposal drifts.

#### Table 4-1: Dimensions of the shafts, galleries and tunnels.

<table>
<thead>
<tr>
<th>Number</th>
<th>Length (m)</th>
<th>Diameter (m)</th>
<th>Concrete Support</th>
<th>Gallery Spacing (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft</td>
<td>2</td>
<td>500</td>
<td>6.2 / 5.0</td>
<td>0.60</td>
</tr>
<tr>
<td>Transport Galleries</td>
<td>5</td>
<td>6000</td>
<td>6.2 / 5.0</td>
<td>0.60</td>
</tr>
<tr>
<td>Disposal tunnels</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat-generating HLW</td>
<td>47</td>
<td>4/5</td>
<td>3.2 / 2.2</td>
<td>0.50</td>
</tr>
<tr>
<td>Spent fuel</td>
<td>6</td>
<td>4/5</td>
<td>3.2 / 2.2</td>
<td>0.50</td>
</tr>
<tr>
<td>Non-heat-generating HLW</td>
<td>36</td>
<td>200</td>
<td>3.2 / 2.2</td>
<td>0.50</td>
</tr>
<tr>
<td>LILW and DU</td>
<td>65</td>
<td>200</td>
<td>4.8 / 3.7</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Figure 4-1-1: Artis’s impression of a geological disposal facility in the Boom Clay.

4.1.3 HLW

The high level waste consists partly of heat-generating waste (vitrified waste from reprocessed spent fuel from the Nuclear Power Plants in Borssele and Dodeweerd, conditioned spent fuel from the research reactors and spent uranium targets from molybdenum production), and partly non-heat-generating waste such as hulls and ends from fuel assemblies that have been disassembled during reprocessing. Heat generation is a result of the continuing radioactive decay of the radionuclides in the wastes. As time progresses, the heat output decreases due to the ongoing decay. The amount of heat generated depends on the type of waste, its composition and/or the burn-up of the fuel. It is expected that some other non-heat-generating HLW will be generated in future, including waste from dismantling and decommissioning nuclear facilities, or historical wastes not yet stored at COVRA. The amount is presently estimated at about 600 tonnes. For the purpose of the OPERA study, it is assumed that this waste is packaged the same kind of canisters as used for spent fuel from research reactors and conditioned with concrete. HLW is expected to require further packaging and/or conditioning before disposal.

4.2 The OPERA geological disposal facility (GDF)

The GDF design used as the basis for OPERA consists of both 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. This depth is considered to provide adequate isolation of the GDF not only from people, but also from the effects of many long-term, dynamic surface phenomena, such as those caused by climate change. The Boom Clay (see Chapter 5) is characterised by its very low permeability to water, meaning that there is no significant flow of groundwater through the formation. Instead, any movement of chemical species towards or away from the GDF will be predominantly by the extremely slow process of diffusion in the pore waters of the clay.

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 – smaller thicknesses might also be feasible. This is in line with previous research in the Netherlands and the Belgian disposal concept [ONDRAF/NIRAS, 2001b: p.15].

## Table 4-1: Expected eventual inventory of wastes for disposal, showing their mass and volume in storage and their mass and volume when packaged for disposal.

<table>
<thead>
<tr>
<th>Waste Category</th>
<th>In storage</th>
<th>Packaged for disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume [m³]</td>
<td>Weight [tonne]</td>
</tr>
<tr>
<td>Processed LILW</td>
<td>45,000</td>
<td>150,000</td>
</tr>
<tr>
<td>TENORM</td>
<td>34,000</td>
<td>110,000</td>
</tr>
<tr>
<td>Vitrified HLW</td>
<td>93</td>
<td>191</td>
</tr>
<tr>
<td>Spent research reactor fuel</td>
<td>104</td>
<td>99</td>
</tr>
<tr>
<td>Other HLW</td>
<td>256</td>
<td>600</td>
</tr>
</tbody>
</table>

**Figure 4-1-2: Disposal sections of the underground facility.**

Construction could use both conventional mining excavation methods and tunnel boring machines. Cement-based materials (concrete) are used extensively in the design, selected using experience in civil engineering over decades to more than a century. This permits a good understanding of the performance of these materials and their possible interactions with the host clay and other EBS materials.

#### 4.2.2 Underground facilities

The underground facilities contain separate disposal sections for the different types of wastes, a pilot facility and a workshop for maintenance work, all connected by a main gallery. The main gallery is an planar structure, which connects with the ground level via two access shafts and/or an (optional) inclined ramp.

The facility contains four waste disposal sections: for vitrified HLW, for spent fuel from research reactors, for non-heat-generating HLW and for the disposal of LILW and depleted uranium (Figure 4-1-2). Each section is optimized with regards to dimensions and modes of transport of the waste containers through the galleries. The proposed dimensions of the shafts and galleries in the OPERA disposal concept are summarized in Table 4-1-1.

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**Figure 4-1-2: Disposal sections of the underground facility.**

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<td>256</td>
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</table>
The layout of the disposal sections depends on the type of waste involved. For non-heat-generating waste, sufficient spacing between disposal drifts is necessary to have a mechanically safe barrier between adjacent zones and to support the overburden.

For heat-generating waste thermal loading is also a consideration. Packages and drift spacing are chosen to limit the temperature in the host rock (typically below 100°C) and engineered barriers, as well as to minimize temperature rise at the interface between any overlying aquifer and the Boom clay.

The vitrified heat-generating HLW and spent fuel (from research reactors) will be packed in contact-handled containers and placed in disposal drifts with a length of 4.5 m. The heat-generating HLW section would allow for modular extension. The non-heat-generating HLW section is longer than the heat-producing HLW section and located between the shafts and the main gallery. The overpacks with the non-heat-generating HLW will be emplaced in 200 m long disposal drifts.

The layout of the disposal section for LLW and TENORM waste is comparable to the non-heat-generating HLW section, except that the diameter of the disposal drift is larger (3.7 m vs. 2.2 m for HLW). To accommodate the larger inventory of LLW/TENORM waste, the number of 200 m long disposal drifts is five times larger than in the non-heat-generating HLW section. Again, the disposal drifts are designed as horizontal dead-end drifts, in order to avoid any water circulation in the unlikely case of flooding of the facility.

The construction of a pilot facility is an important feature of the OPERA disposal concept. The OPERA pilot facility consists of a horizontal boreholes that are directly connected to the main gallery, horizontal drifts, and secondary galleries. Backfill material should not make it impossible to retrieve the waste packages. Furthermore, the backfill material in the heat-generating HLW-section should match the thermal properties of the surrounding clay and enable sufficient dissipation of the decay heat from the container into the Boom Clay.

The suitability of foam concrete as a backfill material has been investigated in OPERA [Vervoort, 2014c]. The length of a single disposal drift in the HLW section is currently assumed to be 4.5 m, including the plug. Each disposal drift can hold 15 supercontainers with a length of 2.5 m, or 12 with a length of 3 m.

In the previous COPRA programme, an inner diameter of 2.2 m was assumed for the disposal gallery for heat-generating HLW to allow worker access to the tunnels [Van de Steen, 1998]. OPERA used the same inner diameter of 2.2 m to accept the supercontainer. In order to maintain stability of the GDF and the containment properties of the clay, the limit of the plastic radius formed around a tunnel excavation in clay was assumed in OPERA to be one-third of the distance between the disposal drifts, the same limit as was used in COPRA [Arnold, 2015a, p.231]. In both COPRA and OPERA only mechanical aspects are considered in the calculation of a safe distance between disposal drifts. Diving to the long pre-disposal cooling period and the use of a supercontainer, thermal load is less restrictive than the mechanical stresses caused by the construction of the disposal drift.

4.2.2.1 Disposal drifts

The disposal drifts in the separate waste disposal sections are horizontal boreholes that are directly connected to the main gallery, in the case of vitrified waste and spent fuel, or can be accessed through the secondary galleries (for other waste types). The disposal drifts are supported by tunnel liners comprising concrete wedge blocks. After the emplacement of the waste packages, the disposal drifts are backfilled with grout and hydraulically sealed, using a plug.

An important characteristic of the backfill is its capacity to provide additional support to the disposal drifts, and, in a later stage, the secondary galleries. Backfill material should not make it impossible to retrieve the waste packages. Furthermore, the backfill material in the heat-generating HLW-section should match the thermal properties of the surrounding clay and enable sufficient dissipation of the decay heat from the container into the Boom Clay.

Data from Belgian Boom Clay samples were used to estimate stresses and resulting plastic radii, as few Dutch samples of Boom Clay taken at a depth relevant for disposal relevant were available in OPERA. Research has been carried out to comprss Belgium clay samples (taken at 200 m depth) to estimate stresses at 500 m depth. The maximum plastic radius calculated with the available data on Boom Clay properties [Arnold, 2015a,b] shows the probability that the plastic radius exceeds one-third of the distance between the galleries is negligible for a distance between galleries of 50 m. With the assumptions made for the analytical model, the limited extent of the plastic zone suggests that the current concept is feasible with respect to geometric stability and that the spacing of the disposal galleries might be reduced.

4.2.2.2 Shaft and tunnel liners

In OPERA, unreinforced concrete segments are proposed for the concrete liner used in the disposal tunnels. Two uniaxial compressive strengths of concrete are considered:

- 45 MPa: similar to concrete used in the Westerschelde traffic tunnel, situated in saline Boom Clay in the Netherlands (reinforced concrete segments: Westerschelde, 2014);
- 80 MPa: similar to the lining of the connecting gallery in the Belgian URT at Mol in non-saline Boom Clay (unreinforced concrete segments: Bastaarn, 2011).

For all cases assessed, the collapse load was not reached for a liner with a compressive concrete strength of 80 MPa and thus the current concept is feasible and a reduction in liner thickness may be possible. However, for a lower compressive strength of 45 MPa the collapse load was nearly reached when increasing the tunnel radius or depth, which may not satisfy design criteria [Arnold, 2015a].

4.2.3 Waste packages

Uniform, standardized waste packages are preferred for emplacement in the GDF. The different categories of HLW will all be disposed in ‘supercontainers’. A key initial objective for the supercontainer was to ensure that the heat generating HLW will be completely contained for as long as it can give rise to increased temperatures in the GDF. However, the supercontainer concept has important further advantages related to the handling of the wastes and these led to the decision to use the same encapsulation method for the non-heat producing wastes. The advantages are:

- The waste canister, overpack and buffer are transported and disposed of as one entity.
- All HLW fractions are enclosed in one standardized container.
- The construction, assembly and quality assurance of the supercontainer can be done above ground.
- The concrete buffer provides shielding to the workers during the operational phase.
- The decay heat is spread over a larger outer surface, simplifying the handling of the heat producing HLW.
- The concrete buffer impedes the corrosion of the carbon steel overpack and the inner stainless steel waste containers.

The OPERA supercontainer is adapted from the Belgian supercontainer concept, which consists of a carbon steel overpack, a concrete buffer and stainless steel envelope, and can hold two HLW canisters or one SF canister. In OPERA, a single supercontainer design is used for all the heat-generating HLW, spent fuel from research reactors as well as the non-heat-generating HLW. Figure 4-1-5 shows an artist’s impression of the OPERA supercontainer for heat-generating HLW.

The OPERA supercontainer is smaller than the Belgian container. The dimensions are determined by the concrete buffer and the size of the waste canister. The supercontainers with a length of 2.5 m hold one canister of either vitrified HLW (CSD-v containers: see Chapter 5) or technological waste from reprocessing (CSD-c containers: see Chapter 5), whereas supercontainers with a length of 3.0 m hold two containers of either spent fuel or other non-heat-generating waste. Future work to investigate in more detail:

- the possibility of another standardised supercontainer for spent fuel will include consideration of the disposal of a single ECH canister containing spent research fuel in each supercontainer;
- the possibility of another standardised container for non-heat generating waste such as CSD-c.

Buffer thickness inside the supercontainer is a balance between transportability and handling inside the facility, retrievability, radiation shielding and heat dissipation, and buffer stability.
Because of the longer interim storage in the Netherlands than in Belgium, heat production and radiation are lower, and package dimensions can be reduced. The container is dimensioned for the heat-generating HLW. The concrete shielding of the OPERA supercontainer is designed to limit the surface dose rate of the heat-generating HLW to a maximum of 10 mSv per hour.

The properties of supercontainers are summarised in Table 4-1. The EBNORM (depleted uranium) is disposed of in KONRAD type II containers.

4.3 How the OPERA disposal system provides isolation and containment

The Boom Clay host rock and the EBS design have been selected because it is expected, based on the considerable precedent, that containers for HLW could be suitable for disposal without further packaging or conditioning. The TENORM (depleted uranium) is disposed of in KONRAD type II containers.

The present section describes how these objectives will be achieved. The function of the subsequent safety assessment of the NES is to demonstrate, on the basis of scientific analyses, that the expectations on containment and isolation are justified. OPERA also examines how other future scenarios might lead to different consequences, although these have not yet been analysed.

The design of the supercontainer is illustrated schematically in Figure 4-3-1. In future, the dimensions and thicknesses of the components (e.g. overpack thickness) may be adapted to optimise containment performance, based on safety assessment results (see Box 4). As can be seen from this illustration, the relative amounts of cementitious material compared to other component are considerable. For the HLW tunnels containing vitrified reprocessing waste, the volumes of materials per emplaced supercontainer (assuming a 5 cm gap between each) are 0.9 %.

Table 4-1.2: Characteristics of the supercontainer design used in OPERA

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer container diameter</td>
<td>1.9 m</td>
</tr>
<tr>
<td>Outer container length</td>
<td>2.5 m for 1 CSD and 3.0 m for 2 ECO (container)</td>
</tr>
<tr>
<td>Waste container</td>
<td>One CSD-1-canister, one CSD-2-canister, or 2 ECO (container)</td>
</tr>
<tr>
<td>Concrete thickness</td>
<td>0.6 - 0.7 m</td>
</tr>
<tr>
<td>Carbon steel overpack</td>
<td>3 cm (to meet a 1000 year containment requirement)</td>
</tr>
<tr>
<td>Stainless steel envelope thickness</td>
<td>0.4 cm</td>
</tr>
<tr>
<td>Max. dose rate at container surface</td>
<td>10 mSv/hr</td>
</tr>
<tr>
<td>Weight</td>
<td>Approx. 20,000 kg, up to max. 24,000 kg</td>
</tr>
</tbody>
</table>

The normal glacial cycling pattern that has occurred throughout the Quaternary period (the last 2 million years) will end by a spike in atmospheric greenhouse gases, such that a major glaciation appears unlikely until at least 100,000 years into the future. The implications of future climate and glacial cycling over the next tens of thousands of years are discussed in Chapter 5 and a deeper study of the possible impacts of human induced climate change will be incorporated into a set of ‘Altered Evolution’ scenarios in future work.

4.3.1 Changing climate

In the OPERA safety assessment, climate evolution is expected since it is recognised that, within the next 100,000 years to one million years major climatic change is to be expected, leading to periods of global cooling, lowering of the sea level and the formation of permafrost. It is expected that mid-latitude ice sheets will form, which might cover the repository area. However, unlikely extremes, such as intensified glaciation with the presence of a massive ice cap, are not part of the Normal Evolution Scenario; these are discussed in Chapter 5.

Over the next 50,000 years, possibly as far as several hundred thousand years into the future, present climate models that include the effects of human-induced global warming suggest that conditions that are either warmer or similar to today will continue. The normal glacial cycling pattern that has occurred throughout the Quaternary period (the last 2 million years) will end by a spike in atmospheric greenhouse gases, such that a major glaciation appears unlikely until at least 100,000 years into the future. The implications of future climate and glacial cycling over the next tens of thousands of years are discussed in Chapter 5 and a deeper study of the possible impacts of human induced climate change will be incorporated into a set of ‘Altered Evolution’ scenarios in future work.

4.3.2 Different possible evolution scenarios

The expected evolution portrayed in the NES is the benchmark for the disposal system. However, other events might push evolution in different directions and their possible impacts will also need to be assessed in future work.
As a result of a comprehensive analysis of FEIs (Grupa, 2017: OPERA-PUI-NEURG1111) and based upon the previous CORA and Belgian SAFIR-2 safety analysis, OPERA identified the following ‘Altered Evolution’ scenarios for future assessment:

- Abandonment of the GDF
- Poor Sealing of the GDF
- Anthropogenic greenhouse gas effects on future climate
- Faulting affecting the geological barrier
- Intensiﬁed glaciation
- Human Intrusion and Human Actions

These are outlined briefly below.

4.4.1 Abandonment of the GDF

The repository facilities and operations will be designed to be fail-safe during all steps of the disposal process. This means that, even in case of abandonment of the repository without proper closure, the waste will not suddenly be released to the surface and present an immediate threat to the environment. Nevertheless, an abandoned and incomplete GDF will not provide the same level of containment and isolation as intended and this possibility needs to be analysed. Unlikely events that might lead to abandonment of the facility include serious economic and regulatory malfunction, war or other national disasters and major mining or underground construction accidents, without proper response. Temporary abandonment would be a recoverable event. In a highly unlikely worst case, involving long-term societal breakdown, events could lead to permanent abandonment of the repository, without proper closure. Such an event was considered in studies (e.g., Grupa, 2000; Grupa, 2009) where it has been assumed that abandonment could lead to flooding of unsealed galleries and earlier exposure of the containers and the wastes to larger volumes of water, compared to the Normal Evolution Scenario, followed by ﬂow and diffusion through the remains of the underground infrastructure (galleries, shafts) and earlier release of radioactive material into the aquifer or biosphere.

4.4.2 Poor sealing of the GDF

A poor sealing scenario was considered in the second Safety Assessment and Feasibility Report SAFIR-2, based on the assumption that the shafts, access galleries and disposal galleries are poorly sealed, e.g., due to construction errors, poor construction materials or errors in the design and testing of the facility and/or the seals. This might result in the formation of a hydrological connection between the an aquifer overlying the host rock and the access and disposal galleries. If pore water pressure in the Boom Clay is higher than in the galleries, water can be squeezed into them, inducing ﬂow through the poor seals of the GDF to the overlying aquifer. Nevertheless, the slow processes of degradation of the engineered barriers and mobilisation of radionuclides from the wastes would be the same as those in the NES and migration and dispersion in the far-ﬁeld will also be similar, so that only limited impacts are envisaged from this scenario.

4.4.3 Anthropogenic greenhouse gas effects on future climate

This scenario considers the changes in the overlying aquifers due to global warming of the atmosphere and analyses the resulting radiological impact. The greenhouse efﬁcacy may cause the present moderate climate to evolve into a warmer, more Mediterranean climate over the coming centuries. In the Belgian SAFIR-2 safety study, the greenhouse effect was assessed to have only a very limited impact on the disposal system, affecting mainly the biosphere and, to a lesser extent, the hydrogeological environment. The scenario speciﬁc to a direct impact on the Boom Clay or the near ﬁeld, and no radionuclides were released into the aquifer during the ﬁrst 5000 years. Therefore, that scenario was excluded from further study in SAFIR-2.

The OPERA evaluation notes that the scenario could lead to an increased risk of ﬂooding of the GDF as a consequence of rising sea-level. As a result, brackish water might inﬁltrate the shallow subsurface or the GDF, if it has not yet been closed. An important difference from the abandonment scenario is the timing of radio-nuclide release to the geosphere and the biosphere and the prevailing biosphere conditions at the time of release, as impacts might occur well after the greenhouse effect has come to an end. This scenario could also consider enhanced transport through the aquifer system compared to the NES and changing chemical conditions, especially in the aquifer affecting the geological barrier.

4.4.4 Faulting affecting the geological barrier

Site characterization will screen carefully for the presence of major faults transecting the repository or the surrounding host rock. However, the possibility of undetected deep faults being present and being reactivated, propagating upwards through the Boom Clay to the surface, cannot be completely excluded at this stage, before any site studies have been performed. The fault scenario considers the consequences of a tectonic fault through the host rock and the repository, which has the potential to form a preferential ﬂow path for radionuclide migration. Owing to the plasticity of the Boom Clay, a sharply deﬁned fault plane might not be formed. Instead, the clay will deform plasticity a broader zone, resulting in a change in the hydraulic and mechanical properties of the clay within the fault zone compared to those of the undisturbed clay. The SAFIR-2 study assumed that a fault forms through the repository, affecting the containment and isolation capacity of the geological barrier. The OPERA evaluation considers potential changes in hydraulic properties in the faulted rocks and possible mechanical processes affecting the waste packages. As with the poor sealing scenario, it is expected that there would be limited impacts compared to the NES.

4.4.5 Intensiﬁed glaciation

During the past Quaternary glacial periods, permafrost developed intermittently in large parts of northern Europe where periglacial conditions prevailed, being estimated to have reached depths ranging from a few tens of meters in the case of the Mol site in Belgium (Marinov, 2000) to 100–300 m in the Netherland, Germany and northern England (Shaw, 2012; Grassmann, 2009). Future, deep permafrost development could have direct impacts at repository depth, including possible impacts on the EBS if it were able to penetrate so deeply. Even if the GDF is at a depth greater than permafrost development, impacts on the host rock and indirect effects such as brine formation and migration, intrusion of freshwater from melting permafrost or glacial ice formed beneath the permafrost layer (Rochelle and Long, 2009), and cryogenic pore pressure changes associated with volume change during the water-ice phase transition could affect the integrity of the geological barrier. These processes might affect the transport processes of any released radionuclides. In addition, an intense glaciation with thick ice sheet development over the GDF site could lead to localised deep erosion. This possibility is discussed in Chapter 5. The intensiﬁed glaciation scenario identiﬁed in OPERA assumes the presence of a massive ice sheet producing meltwater, deep subglacial erosion and thick permafrost development in front of the ice sheet.

4.4.6 Human Intrusion

Future actions of people that might affect the integrity of a GDF after its closure and potentially give rise to radiological consequences are known as ‘human intrusion’ (IAEA, 2012: p.79). The scenario of human intrusion is one in which all barriers – both engineered and natural – are short-circuited. Human intrusion may lead to increased release of radioactive material and increased long-term exposure of individuals or groups around the disposal facility. IAEA SSG-23 recommends that only inadvertent (unintentional, as opposed to intentional) human intrusion should be considered, assuming that it will occur at some time following the loss of knowledge about the site and its hazardous contents (IAEA, 2012, p.88). The IAEA recognizes that the relevance of human intrusion scenarios for geological disposal facilities is limited, as the depth and location of such facilities make human intrusion unlikely. In addition, the time frames of concern are judged too large to enable meaningful estimates of possible impacts from intrusion events. The IAEA nevertheless recommends assessing the consequences of human intrusion, in order to demonstrate the robustness of the disposal system.

The most likely activity leading to human intrusion is deep drilling, for example, as a result of exploration and production drilling for oil and gas, geothermal energy, energy storage or deep wells (over several hundred meters) for water extraction. Mining of the host rock material itself is highly unlikely, since clays of the same or better quality are easily accessible and locally available from surface mining. The OPERA evaluation suggests that locally degraded properties of the engineered barriers and some waste packages would need to be assumed at the time when drilling occurs.

4.5 What-if scenarios

In order to test and illustrate the containment and isolation functions of the individual barriers in the multi-barrier system, it is useful to carry out other analyses that are not based on the expected behaviour of the system. Such analyses, identiﬁed from a raw list of FEIs, ask simple ‘what-if?’ questions, without necessarily speculating how a situation might occur, or indeed, whether it could occur at all. The OPERA study identiﬁed a range of speculative ‘what-if’ scenarios, some of which can be considered in future work:

- Early supercontainer failure, which might be caused by a defective overlap. In some national safety assessments, this scenario has been a central case for analysis rather than a ‘what-if’ case as, despite considerable advances in manufacturing quality control over recent decades, it could be difﬁcult to ensure complete integrity of each of the large number of containers in the GDF at the time of disposal.
- Nuclear criticality leading to excessive heat production.
- Compaction of the Boom Clay by glacial loading resulting in increased porewater movement.
- Enhanced microbiological effects on the EBS and host rock.
This Chapter looks in more detail at the geological environment in which the GDF will be constructed and where it will evolve slowly with the passage of time. The host rock for the GDF, the Boom Clay formation, and the overlying geological formations back to Earth’s surface comprise the natural barriers within the multibarrier system concept introduced in Chapter 2. These are described in Sections 5.1 and 5.2. Because the properties and behaviour of the natural barriers can be affected by major changes in Earth’s surface environment, principally as a result of climate change, Section 5.3 introduces these dynamic processes and discusses their potential impacts.

5.1 The Boom (Rupel) Clay

The Boom Clay is the host rock for the GDF, the principal natural barrier and the most important barrier in the complete multi-barrier system, in that it not only itself contributes strongly to retention of radionuclides, but also because its properties control the behaviour and performance of all the engineered barriers in the system. The Boom Clay dates from the Oligocene Epoch around 30 million years ago and it is expected that its stability is such that it can isolate the waste from people and environment for at least one million years, by protecting the disposal facility from potentially detrimental natural processes.

The Boom Clay is a marine clay formation that was deposited as seafloor sediment during the Rupelian stage of the Paleogene period, between 33.9 and 28.1 million years ago, in the southern part of the North Sea basin, of which the London-Brabant Massif was the southern limit. The London-Brabant Massif includes the

5. The Natural Barrier System

How nature can isolate the waste from people and the environment for at least a millions years

In the course of a GDF development programme all of the positive characteristics must be measured in detail as well as other key properties that influences performance, such as its homogeneity, heat transport, etc.

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present-day Ardennes Mountains. At that time, the coastline was located in present-day Belgium, with the sea deepening towards the north, as shown in Figure 5-2-1. It can be seen that the Boom Clay was deposited much of the of the present-day Netherlands and much of Belgium.

5.1.1 Thickness and depth

The present thickness of the Boom Clay has been affected by tectonic uplift and erosion. In the Oligocene epoch, the formation was eroded in the western part of the Netherlands and, near the province of Zeeland, continuous uplift of the London-Brabant Massif resulted in the deposition of a thinner sequence [Vis, 2014/2016]. In some areas, deposition of younger sediments has protected the underlying Boom Clay from further erosion.

In OPERA, studies have been made [Vis, 2014] to deduce the depth and thickness of the Boom Clay formation, using data from oil and gas wells that are publicly accessible in the framework of European Directive INSPIRE [EU, 2007]. However, high-quality logs and cores are usually not reported from oil and gas wells penetrating the Palaeogene clay layers [Vis, 2016], so there are uncertainties, but the general regional corrections made are less than 40 m for the top and bottom of the Rupel (Boom) Clay member. Figure 5-2-2 shows the top of the Rupel (Boom) Clay Member (left) and its geographic residual variation (right). Figure 5-2-3 shows the estimated thickness distribution of the Boom Clay (left).

It can be seen that the Boom Clay is present in a potentially appropriate depth range of 300 to 600 m across large parts of the NW and SE Netherlands, in potentially appropriate thicknesses of >50 m below the fresh-brackish groundwater interface. For OPERA, a generic case was selected with the GDF at 500 m in a clay layer 100 m thick. It is emphasised first that the OPERA work illustrates that there are significant geographical uncertainties in the Boom Clay depth and thickness distribution (as discussed in report and, second, that OPERA has made no attempt to consider optimising appropriate depths and thicknesses, so these numbers are indicative only. However, the important observation is that potentially useable host rock for further research is relatively widespread.

5.1.2 Natural radioactivity of the Boom Clay

There are natural radionuclides in Boom Clay and there is evidence of the containment potential of the clay for these elements, in particular with respect to its natural uranium and uranium daughter radionuclide content. In the previous research programme (CORA), the assumption was that the uranium concentrations in clay found at the surface are representative for Boom Clay at disposal depth [Graaf van der, 1998]. OPERA has measured the chemical content of trace elements in Boom Clay, including uranium and several chemical analogues (i.e. natural elements that behave chemically in a similar way to artificial radionuclides such as Nd, Sm, Zr and Se [Keenen, 2014/2016]). The natural radiation contribution to the aquifers surrounding the Boom Clay can be used as a yardstick to compare any additional radiation contribution that might arise from the disposal of the waste (see Chapter 8).

5.1.3 Water movement in the Boom Clay

The main safety function of the Boom Clay is to delay and attenuate the potential release of radionuclides from the engineered barrier system by limiting water flow into and through the GDF. This is achieved through the very low permeability of the clay, in which pore water is effectively stagnant (i.e. no water movement) so that diffusion can be assumed to be the dominant process by which species can move through the clay, under the influence of a concentration gradient. Key factors affecting the safety case assumption of diffusive movement, rather than water flow, are the hydraulic properties of the clay at relevant disposal depth, discontinuities in the clay that might act as pathways for flow and the potential impact of ice loading on the properties of the Boom Clay.
5.1.3 Discontinuities as potential flow pathways

The Boom Clay is sufficiently plastic in behaviour that it does not contain discontinuities such as open fractures that could act as pathways for water (and radionuclide) movement. However, it is possible that such discontinuities could form temporarily, by seismic activity, by gas movement through the Boom Clay, or by construction of the GDF. However, in the Belgian programme, fractures induced by excavation have been observed to seal within weeks [ONDRAF/NIRAS, 2013: p.33] and were not considered to be a significant issue in the OPERA safety case.

Seismic activity, possibly leading to large magnitude earthquakes, might be caused by unloading during the retreat of a future ice sheet at the end of a future glaciation. As discussed in Section 5.3, glaciations are likely to occur in the next million years. Such activity is expected to be concentrated in the main fault zones already present in the Netherlands [ten Veen, 2015: p.56]. Re-activation of such faults could cause significant fracture propagation through the Boom Clay, with fractures larger than those induced by excavation. Vertical displacement of a part of the Boom Clay formation and its surrounding rock formations might occur. However, hydraulic analyses performed in OPERA show little impact of such faults on pathways for water (and radionuclide) movement. However, it is critical to consider and avoid geological situations where potential zones of weakness in the Boom Clay.

5.1.3.3 Effects of ice loading on water movement in the Boom Clay

Ice-sheet loading at Earth’s surface can affect hydraulic conditions in the Boom Clay at depth and potentially result in water movement in the clay. The measured over-consolidation of a sample of Boom Clay at a depth of 433 m in the north of the Netherlands [Blija] of between 1.3 and 1.8 has been attributed to diagenesis and creep processes, as well as to the clay being subjected to a higher loading than it is at present [Wilderhorst, 2000: 2003]. In OPERA, no in-situ measurements or measurements on fresh Boom Clay cores taken at relevant disposal depth have been made, but samples stored under dry conditions have been used. In the previous research programme (CORA), cyclic ice loading was modelled and was found to result in significantly higher radionuclide mass fractions at the boundary between the clay and surrounding aquifers than without an ice cover. A maximum outflow rate of water from the Boom Clay was assessed to be 1 mm per year, three orders of magnitude higher than the flow rate without ice loading [Wilderhorst, 2003]. This type of analysis has not been performed with the model developed in OPERA, so this potential effect has not yet been studied further.

The modelled ice-sheet thickness in CORA was 1000 metre and is now considered unrealistically large, based on the research performed in OPERA. Usually, evidence of ice-sheet loading can be provided by the measured over-consolidation of clay only for the last ice coverage, as the excess pore pressure dissipates slowly enough to observe the remnants of the load. For the Saalian glaciation, the ice-sheet thickness in the northern part of the Netherlands was estimated to be only 195 m, and in the Saalian glaciation, 200 m in the northern part of the Netherlands [Verweij, 2016b]. These were the last two glaciations to cause significant ice cover in the Netherlands. Modelling of these loads shows that over-pressure in the Rupel Clay would still persist today, but this is critically dependent on formation thickness: i.e., the decay time is about 160,000 years for a thickness of 100 m, 630,000 for 200 m but only 40 years for a thickness of 50 m. Thus, in order to understand the over-consolidation values of between 1.3 and 1.8 measured in the CORA programme, the thickness and hydraulic properties of the Rupel Clay formation from which the sample has been taken, need to be known.

The benefit of over-consolidation is that, as the load is removed, there is a hydraulic potential for inward advective flow – in other words, the clay formation would take in water from surrounding aquifers and not be able to advect radionuclides out from a GDF.

5.1.4 Mineralogy and retention properties of the Boom Clay

The mineralogy of the Boom Clay was measured in OPERA using XRD analysis on 30 samples from seven boreholes [Kaonen, 2014]. Most samples were taken from the TNO core store and have been stored dry for several years, leading to some secondary gypsum formation by pyrite oxidation. The effects of drying have been corrected in evaluating the mineral content [Griffioen, 2017]. Table 5–2–1 shows the average mineralogy of Dutch Boom Clay compared to the Belgian Boom Clay and the Swiss Opalinus Clay (also deposited as marine clay). Owing to its greater age, the Opalinus Clay has a higher illite content and a smaller smectite and feldspar content than the Dutch Boom Clay. Apart from some early-diagenetic processes in shallow burial environments, the Boom Clay mineralogy can be assumed to be deposited 30 million years ago.

The Boom Clay displays a strong retention or retardation capacity for many radionuclides owing, for example, to its high sorption capacity and favourable geochemical properties. The retention capacity of Boom Clay is assumed to be controlled by sorption of dissolved complexes on minerals surfaces or on organic matter, but...
the salinity. The salinity of the Boom clay pore water is likely to be from 4 to 20,000 mg/l [Schröder, 2017: p.26: NRG7251], i.e., the dissolved organic matter content in the pore areas. For most areas in the Netherlands, water from a depth of 5.1.5 Porewater composition

Experimental data for pore waters can only be taken from fresh cores or in underground labs. In OPERA, the only fresh Dutch Boom Clay sample available was taken at 70-80 meters depth near CORA’s premises in Zeeland. Data were also available from core cuttings in Limburg. The measured CECs were in the range reported for the Belgian Boom Clay [Behrends, 2015: p.28]. In OPERA, a range in CEC between 2.0 and 4.20 meq/g is assumed in order to determine its effect on clay [Schröder, 2017: NRG7251].

Dissolved organic matter (DOM) can be divided into a mobile and immobile pool. The mobile pool can be collected in piezometers and, in Belgian Boom Clay, is dominated by species with a hydrodynamic radius smaller than 2.8 nm [Durce, 2016: p.31]. The immobile pool is only present in leached fractions and is largely preserved from migrating in the clay by colloidal filtration. Provided the mineralogical assemblages between Dutch and Belgian Boom Clay did not differ, the hydrodynamic radius for colloidal organic particles is expected to be smaller due to its larger depth of solution i.e. more compaction. Generally, the mobile pool is smaller in the Dutch Boom Clay. However, this potential positive effect of a larger depth of disposability is conservatively not included in the OPERA assessment. OPERA considers the results of recent experiments to evaluate how dissolved organic matter in pore waters is removed from solution by flocculation and coagulation. In the presence of Boom Clay there is no difference in loss of DOM with increasing ionic strength for either NaCl or CaCl2 electrolytes [Durce, 2016: p.39]. It is noted by flocculation and coagulation. In the presence of Boom Clay there is no difference in loss of DOM with increasing ionic strength for either NaCl or CaCl2 electrolytes [Durce, 2016: p.39]. It is noted that pore water DOM has not been measured in OPERA so, in the assessment, three cases of DOM content are assumed to span the range suggested [Schröder, 2017: NRG7251: p.26].

Pore water composition of Boom Clay is expected to remain stable after about 105 years, with a low likelihood that could be mitigated by disposal of waste in Boom Clay in context. The speciation of disposal of waste in Boom Clay may result in more rapid transport of radionuclides through the Boom Clay. The chemical effect of such deep erosion may result in more rapid transport of radionuclides through the Boom Clay. In the case of previous deep incisions by tunnel valleys in the Elsterian glaciation, deep, sub-ice, erosional tunnel valley systems developed. If this were to occur in future, fresh water into the Boom Clay is calculated for a period of 10,000 years [Vandenberghe et al., 2014]. The formations surrounding the Boom Clay are thus dominantly sands and clays, with variable thicknesses of sand, silt and clay [Vandenberghe et al., 2014]. The Boom Clay lies above the sandy Vessem Member, which is variable in thickness but present in nearly the whole onshore part of the Netherlands. Over most of the onshore area, the Vessem Member consists of silty to clayey sands with a low or zero carbonate content. In some areas, the Boom Clay overlies the Tongeren and Dongen Formations, which also consist of alternating sand and clay layers.

In the southeast of the Netherlands, the Boom Clay is overlain by the sandy Steensel Member, which consists of alternating sands and clays with thin sand layers, grading upwards into fine-grained sands, reserved in a near-coastal environment. Further north, the sandy Steensel Member is absent and the similarly sand-dominated Voort Member overlies the Boom Clay. In the rest of the country the Boom Clay is covered by the Veldhoven Clay Member and the Breda Formation, which is generally clay-dominated in the north and contains sandy intercalations in the south. In Zeeuws-Vlaanderen, where the Boom Clay lies at shallow depths, it is covered by Quaternary deposits.

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groundwater. In order to evaluate the transport of radionuclides from the Boom Clay to the surface, OPERA has used measurements and assumptions made for the existing national groundwater model of the National Hydrological Instrument (NHI). This model has been set up for addressing national water policy issues, such as drought management, agricultural fertiliser use policy and climate impacts on water supply, including assessment of future drinking water supply in 2040 (RIVM, 2015). The NHI model includes some of the formations overlying the Boom Clay, but does not extend down as far as the Boom Clay at relevant disposal depths. For OPERA, the NHI model has been extended into a steady-state model that takes into account saturated groundwater flow in the west and central part of the Netherlands is taken to be at around 200 m depth in the NHI model.

Valstar [2017] modelled potential groundwater flow paths to the surface in the extended NHI model. Fast pathways through the aquifer formations above the Boom Clay have a calculated residence time of about 30,000 years under present day climate conditions. Medium and slow pathways have calculated residence times greater than 100,000 years. For each pathway, also a pathline length was determined [Valstar, 2017: p.37]. These calculated pathline lengths were divided by the residence times in the overburden to determine the effective groundwater flow velocity to determine the transport of radionuclides in the overlying formations [Schröder, 2017:NRG7251: p.33].

Substantial dilution will reduce the concentrations of any radionuclides from the GDF that are released from the Boom Clay and enter the overlying formations. The extent of dilution would depend on the number of aquifers that are encountered and the flow rates in them. A thin plume or migrating radionuclides is expected to form in the overlying sandy aquifer, due to the large horizontal flux in the aquifer compared to the small vertical flux out of Boom Clay. The model conservatively assumes homogeneous aquifers properties, rather than internal layering of more and less permeable units within formations. In the extended NHI model, those formations with aquifers are present between the surface and Boom Clay and calculated radionuclide concentrations are reduced around 1% of the value leaving the Boom Clay by transverse mixing [Valstar, 2017: p.39].

5.2.1 Parameter values for OPERA

For the results presented in this OPERA safety case, the residence times fast pathway with a residence time of about 30,000 years in a moderate climate is used. For the interface from the overburden to the biosphere, it was recognised that the water flux through the overburden has no relation with the travel time. The water flux from the Boom Clay into the overburden is 4500 m³ per year and the water flux from the overburden into the biosphere 20250 m³ per year is a dilution factor of 4.5 i.e. the small dilution case [Valstar, 2017: p.85] or little dispersion case [Schröder, 2017: NRG7251: p.34].

5.3 The potential impact of climate change on the natural barriers

The Quaternary Period (approximately the last 2.5 million years) is characterised by cyclic glaciations affecting the northern hemisphere roughly every 100,000 years, with intervening warm periods (interglacial) such as that prevailing today, in which modern humans have progressively populated the whole of northern Europe.

The last glacial period (the Weichselian) peaked about 25,000 years ago, with warmer conditions setting in over the last 10,000 years (the Holocene Epoch). 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. The growth and decay of ice sheets, their movement and the hydrological conditions beneath them, can affect the geological formations beneath them in terms of the deep and shallow groundwater flow regime and by erosion. Sea levels are also affected by the response of the land surface to ice loading and unloading.

However, 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. OPERA has considered the last three glacial cycles, which have occupied approximately the last 500,000 years. The extent of ice cover and melting processes in the Elsterian (475 - 410 ka ago), the Saalian (170 - 130 ka ago) and the Weichselian (115 - 10 ka ago) glaciations is shown in Figure 5-3-1.

A central concern in siting the Dutch GDF may be to avoid the possibility for deep erosion in a future intense glaciation. As in the previous CORA research programme, OPERA assigns a depth of 500 metres for the generic GDF, in order to take into account the possible erosion that might be caused during the retreat of future ice-sheets, but has so far not looked into the most appropriate approach to use in future siting work [Verhoef, 2014b]. Assessing this scenario will involve considering how deep erosion can occur, when it might occur and the likelihood that any given area might be affected. Previous research programmes have looked at the evidence for how deep erosion has occurred in the past.

The first Dutch geological disposal programme, OPLA, introduced the term SubGlacially formed Deep Depressions (SGDD) for such erosion [Groot de, 1993]. As ice melts at the end of a glacial period, melt water is released at the base of the ice sheet at a rate that will depend on change in air temperature at the base of the ice sheet. In the Elsterian transition from the glacial to interglacial climate, the temperature rise was assumed to be larger than in the Saalian. Consequently, melt water production rate was larger [Dijke van, 1996] and SGDD - nowadays called tunnel valleys – were formed in unconsolidated sediments in the northern area, dominantly in what is now the offshore area beneath the present-day North Sea. The Elsterian tunnel valleys are typically about 100 to 200 m deep, with a maximum depth of 400 m.
In OPERA, interpretation of a seismic profile of one such Elsterian tunnel valley shows that erosion was deep enough to intersect the Boom Clay at a depth up to 600 m (Figures 5-3-1 and 5-3-2). However, the Saalian glacial basins are rarely deeper than 150 m [Dijke van, 1996].

In the most recent, Weichselian glaciation, no part of the Netherlands was covered by ice, but permafrost conditions developed extensively, in which soils and the overlying sediments above the Boom Clay were frozen to varying depths. Owing to the difference in latitude, the depth of the permafrost is expected to have been somewhat larger in the north than in the south of the Netherlands. OPERA has investigated the potential for future permafrost development, taking account of the geothermal flux and the average sand content of the overburden. For any location in the Netherlands, the depth of permafrost would be between 120 - 200 m and not greater than 270 m, not deep enough to affect the GDF itself [Govaerts, 2015:p.42].

The potential for future post-glacial seismicity also needs to be considered. The suppression of seismic activity during periods of ice cover stores up stresses until the ice melts, which itself also causes a reduction in load on the lithosphere. Consequently, earthquakes can occur, with movement on existing faults in the period immediately following glacial retreat. Such seismic activity is expected to be concentrated in the main fault zones already present in the Netherlands [ten Veen, 2015:p.56].

All of the processes discussed above would only occur some time into the future during and mainly in the closing stages of a glaciation. A central question is thus whether a future glaciation might occur, as the current Quaternary glacial cycle, principally caused by variations in Earth’s orbital behaviour, is expected to continue. A key aspect of this question is the effect that human activities, in particular our greenhouse gas emissions, are having on the climate. It is expected that these will continue to cause a rise in temperatures and a reduction in the extent of the summer’s snow and ice. It is then possible that we may have a glacial period again in the future where some of the ice sheets which are at present in the north and north-eastern provinces of the Netherlands [ten Veen, 2015:p.54] will advance again. However, it is not believed that this will happen soon, and if warming stops, it may not happen at all.

5.3.1 Assumptions for the post-closure safety assessment

Erosion induced by the change in climate from a glacial to an interglacial state is considered the only potentially detrimental process in a normal evolution of a disposal system with a facility in Boom Clay at relevant disposal depth. Prediction of global climate trends with orbital parameters suggest that in a next glacial period there is a fairly high probability for ice–sheet margins to reach down to the north and north-eastern provinces of the Netherlands. However, it is assumed that glacial inception would be delayed by the warming effects of atmospheric CO₂ levels caused by future emissions on the inception time of the next glaciation. If mankind ultimately burns 2000 Gton C cumulative emissions, which is only slightly above the present-day value, the evolution of the Boom Clay atmospheric ice sheets is affected over tens of thousands of years. In the 1,000 Gt C scenario, the probability of glacial inception during the next 100,000 years is notably reduced, and under cumulative emissions of 1,500 Gt C, glacial inception is very unlikely within the entire 100,000 years. This confirms our conclusions from the critical insolation threshold for glacial inception. Because all 2013 Intergovernmental Panel on Climate Change scenarios—except Representative Concentration Pathway 2.6 (RCP2.6), which leads to the total radiative forcing of greenhouse gases of 2.6 W m⁻² in 2100—imply that cumulative carbon emission will exceed 1,000 Gt in the twenty-first century, our results suggest that anthropogenic interference will make the initiation of the next ice age impossible over a time period comparable to the duration of previous glacial cycles. Overall, the majority of recent studies suggest that there will be a prolonged interglacial period, possibly out to over 100 ka, unless CO₂ emissions are drastically controlled. Whether this is even feasible is a matter of opinion.

The thrust of this discussion is that, although it would be sensible to consider the possibility of deep erosion in a future GDF siting programme, it will be essential also to look in more detail at the likelihood and consequences of such a scenario. If this is a process that could not affect a GDF until some time after 100,000 years, then consideration of Box 2-1 shows that the hazard potential of the HLW will already have been markedly reduced and, as will be considered in Chapter 9, any mobilisation of residual activity from the GDF should be set in the context of the large scale remobilisation of naturally occurring radioactivity in surface sediments by the large rivers and sub-glacial waters that will exist as an ice-sheet melts.

The OPERA post-closure safety assessment makes the simplifying assumption of a constant interglacial climate for a period of 10⁴ 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.

5.3.2 Identification of uncertainties

Inclusion of glacial climates would result in more representative calculations for a period beyond 10⁴ years. This is considered most appropriately dealt with in future scenario analysis work, rather than in the normal evolution scenario. None of the erosion processes has been included in OPERA at this stage. As with the aspects of climate state affecting groundwater flow mentioned above, erosion is also most appropriately dealt with in future scenario analysis work, rather than in the normal evolution scenario. The potential impact of erosion is a shorter residence time and smaller dilution in the overburden. However, as discussed above, such an analysis would also need to account of the huge amount of transport and erosion by rivers in a periglacial climate, leading to a large dilution factor for the eroded waste.
6. The Engineered Barrier System

This section describes the materials, safety functions, behaviour and evolution of the components of the engineered barrier system in the disposal tunnels. Several components of the EBS are common to each of the designs of disposal tunnel for the different types and waste packages discussed in Chapter 4. For example, all sections of the disposal area use similar tunnel linings and foam concrete backfill, and the supercontainer components and materials are the same for all HLW types and spent fuel. Consequently, the functions and performance of these components are grouped and considered together in the following description.

The dimensions and relationships of the EBS components for the main parts of the GDF are summarised in Figure 6-3-1 below. The EBS provides both physical and chemical containment of the radionuclides in the wastes and lies within the stable clay formation, with no movement of groundwater or natural hydraulic conditions having been re-established. Some decades after closure, the porewaters of the Boom Clay will have permeated into and saturated any porosity in the EBS components that was not already filled with water and the whole near-field system will evolve thus have a major influence on the behaviour of all the waste materials and are dealt with first in this description.

The properties of these cementitious materials and the way in which they evolve thus have a major influence on the behaviour of all the waste materials and are dealt with first in this description.

6.1 Tunnel liner and tunnel backfill

The tunnel liner is installed as tunnel excavation progresses and is essential to support the low-strength Boom Clay tunnels at disposal depth. The tunnel backfill is emplaced after waste packages have been emplaced to fill the void space in the tunnels. Together, the liner and backfill comprise the largest volume of cementitious materials in the GDF.

6.1.1 Tunnel liner

The tunnel liner comprises pre-fabricated, interlocking blocks of concrete that are installed as tunnel excavation progresses. The suggested concrete recipe is that currently used for the Westerschelde traffic tunnel in Boom Clay, which is exposed to seawater conditions. As seawater has a high concentration of sulphate, the wedge blocks in the liner will be made with sulphate-resistant concrete. Porewaters from the Boom Clay is expected to migrate freely through the joints between the concrete segments so the liner does not limit water flow in the GDF.

The liner provides mechanical support for the tunnels during the operational phase. After waste emplacement, tunnel backfilling...
and eventual closure, this support function becomes unimportant and overburden stresses will be transferred from the surrounding geological formations through the liner onto the mass of the EBS materials in the tunnels.

Water can permeate from the Boom Clay through the joints between liner blocks and through their porosity. Observations in the Mol URL show that, under open (equivalent to operational) conditions, normal ventilation removes this water and leaves deposits of minerals on joints and liner surfaces. It is expected that, under post-closure conditions interaction of the Boom Clay pore waters with the liner cement will lead to some clogging of joints, affecting the rate at which the EBS saturates. However, the period to re-establishment of saturated conditions and natural hydraulic gradients is expected to be only a few years to decades.

6.1.1 Interaction of the tunnel liner with the Boom Clay

Pore waters in the Boom Clay will interact with those in the liner porosity and with the cementitious materials of the liner. The higher pH pore water of cementitious material will exchange with the more neutral pH of the pore water of Boom Clay, resulting in a halo of alteration in the near-field Boom Clay at an ‘alkali disturbed zone’ (ADZ), which can cause a local reduction in sorption of alkaline earth elements and a 20% local decrease in hydraulic conductivity in Boom Clay, due to calcite precipitation [Seeratham, 2015]. In the Belgian programme, this ADZ interaction is expected to determine [DINRAF/NIRAS, 2013] to mobilise some non-mobile natural organic matter in the clay. No experimental studies of the ADZ are yet available under the saline conditions of the EBS in the Netherlands. Data from the Mol URL (Belgium), suggest that an ADZ (with a pH larger than 8.5) of about 1-3 m will develop in the Boom Clay [Seeratham, 2015] under normal evolution conditions. In the Netherlands, possible future ice loading might increase the extent if any advection flow would develop in the Boom Clay, in OPERA, a larger ADZ is calculated than estimated for Mol, but this study assumed a highly conservative, infinite cementitious source without cementitious minerals [Erfkoven, 2017: p.58].

The suggested cementitious material for the concrete tunnel liner in OPERA contains no portlandite and the cement pore water is assumed to be in equilibrium with the C-S-H phases, leading to a homogeneous distribution of radionuclides within each of the EBS materials and calculating transport processes only once radionuclides have left the EBS and entered the surrounding Boom Clay. Within the EBS, a ‘dissolution volume’ approach is used to determine the radionuclide concentration at the interface between the tunnel liner and the Boom clay [Schröder, 2017: NRG7251] and a diffusion value is allocated to determine the transport of radionuclides across this boundary. Conservatively, a pure diffusion value is allocated similar to that measured for highly mobile tritium in Boom Clay at Mol (Belgium) and a value of 3 x 10^-10 m^2s^-1 is assumed. A time-dependent porosity is assumed: 0.35% for the backfill and 0.15% for the concrete liner. [Schröder, 2017: NRG7251].

In Boom Clay the ADZ is not modelled explicitly in the normal evolution scenario, although its effects are subsumed within the range of pH values used in deriving Boom Clay transport properties.

6.1.4 Uncertainties and further work

Further research on the ADZ is taking place in the EU research project Cebama, in which the time–dependency of a change in permeability and interconnected porosity at the interface between Boom clay and concrete is investigated. In the Dutch contribution, experimental research is being performed on foamed concrete made with Portland cement, as well as blast-furnace slag cement. Calcite precipitation results in a decrease in permeability in Boom Clay [Seeratham, 2015] by pore clogging and further validated in order to make a more realistic and less conservative assessment of the movement of radionuclides in the cementitious engineered barrier system, into the Boom Clay.

Demonstrating experience of the integrity of the suggested cementitious materials for the GDF will grow in the next decades, based on underground constructions already established in the Netherlands and other countries. By the expected time of disposal in the Netherlands, samples might have been taken from the Westerschelde tunnel (in saline Boom Clay) in the Netherlands and the Mol URL in non-saline Boom Clay in Belgium in order to investigate the potential increase in porosity by dissolution of the cementitious phase and consequently its reduction in compressive and tensile strength. Compressive strength measurements have been and will be performed as a Dutch contribution to the EU research project in Cebama.

The maximum thermal conductivity of foamed concrete is 0.80 W m^-1 K^-1 [EUR, 1995], but the Belgian programme sets a minimum value of 1 W m^-1 K^-1 for the backfill [Hummel, 2007]. However, the storage period for heat-generating waste in the Belgian programme is shorter than in the Dutch programme, leading to a difference in thermal power of vitrified waste at the time of emplacement of almost an order of magnitude [Kunsten, 2015]. The Belgian requirement is to prevent the supercontainer exceeding 100°C [Weetjens, 2009]. The minimum in thermal conductivity for the backfill thus needs to be substantiated in the Dutch context.

6.2 The waste packages

In OPERA, significant effort has been expended in order to document a complete inventory of the wastes that will be emplaced in the GDF. This inventory is more comprehensive and detailed than has been used in past work. It is an important starting point for all ongoing and future COVRA activities including present waste handling operations, GDF design work, and also operational and long-term safety assessments. For this reason, the OPERA inventory is described at some length in the present section.

The various packages in which the wastes are conditioned and/or stored are shown in Figure 6-3-2. The container used by COVRA is that, in storage, wastes are held in containers, which are then referred to as canisters if they are welded closed. The figure shows all the LLW (left) and HLW (right) waste streams and the different types of containers and canisters in which they are stored prior to packaging for disposal. When these containers/canisters are placed in overpacks, only four types of disposal packages are produced for emplacement in the GDF:

- Supercontainers for HLW, which hold either CSD or ECN containers
- 1000 litre concrete or magnetite containers for LLW;
- 200 litre drums for HLW;
- Konrad Type II containers for depleted uranium.

As discussed earlier, none of the containers shown in Figure 6-3-2 has been assigned any post-closure containment role. The only such function is assigned to the overpack in the HLW supercontainers, as discussed in Section 6.2.1.
The construction, assembly and quality assurance of the supercontainer can be done above ground. The concrete buffer provides shielding to the workers during the operational phase. The decay heat is spread over a larger outer surface, simplifying the handling of the heat producing HLW. The concrete buffer impedes the corrosion of the carbon steel overpack and the inner stainless steel waste containers.

OPERAs uses a concept similar to the Belgian supercontainer, but uses a single, uniform design of supercontainer for disposal of both heat-generating as well as non-heat generating HLW. Figure 6-3-3 shows an artist impression of the supercontainer used for disposal of vitrified HLW in CDC-v containers. Access of porewaters to the waste is prevented as long as the concrete steel overpack can sustain the mechanical and thermal stresses and resist failure through corrosion. In the Belgian programme, a 30 mm thickness of carbon steel was suggested: 16 mm of which is necessary to sustain the mechanical and thermal stresses, and 14 mm to sustain corrosion [Craeye, 2010]. At the greater disposal depth evaluated in the Netherlands (but lower thermal stresses owing to long cooling), a thickness of 30 mm is calculated to sustain these stresses [Barnichon, 2000]. An overpack thickness of 30 mm has been used in OPERA (see Table 4-1-2). A larger thickness to accommodate the additional loads caused by ice cover during glaciation is unnecessary, because the safety function of the supercontainer is required only over a relatively short period, long after any future glaciation might occur.

In the normal evolution scenario, corrosion will eventually result in loss in integrity of the overpack safety function. The main goal of the Belgian RD&D programme is to provide confidence that this does not occur while the waste generates significant heat. However, the overpack could continue to provide complete containment for much longer than this. The actual longevity of the overpack will depend on the evolving environmental conditions to which steel is exposed, referred to as the Corrosion Evolutionary Path (CEP). OPERA has considered a schematic of CEP with various degradation modes [Kursten, 2015] occurring during three time periods, from fabrication of the supercontainer up to loss of the overpack integrity. The temperature increase in the Boom Clay is limited to 25 °C after 20 years and a peak 50 °C increment at the interface of the overpack after 9 years. The lower thermal conductivity of foamed concrete could result in a smaller temperature increase in Boom Clay and a higher peak temperature. The greater thickness of the concrete liner at the 500 m disposal depth considered in OPERA would have a similar, incremental effect.

The unsaturated period (1) has been calculated to last about 2 years and will depend on the balance of hydraulic conductivity and porosity of the liner and the (eventual specification for) foamed concrete backfill, and that of the Boom Clay [Kursten, 2015]. Oxygen will be consumed principally by corrosion of steel. Some can also be consumed by the concrete buffer under the high radiation flux conditions around vitrified HLW containers. Oxygen consumption by steel corrosion is fast, such that, after one year, reducing (anaerobic) conditions may be assumed at the overpack surface [Craeye, 2010]. Consequently, anaerobic conditions (Period 3) are expected to prevail in the EBS after only a few years. The maximum uniform corrosion rates under alkaline anaerobic and alkaline aerobic conditions have been estimated to be 0.2 and 2.2 μm per year, respectively [Kursten, 2015]. Localised corrosion (pitting, crevice) can be excluded under alkaline chloride-free conditions during the aerobic phase. Chloride-free conditions at the overpack can be assumed in the aerobic phase. In addition, so long as the buffer remains intact, its migration properties are favourable for preventing ingress of aggressive anions from the Boom Clay pore waters that could also cause corrosion [C1, SO4, V, O3, H5, HS, S1]. Protection of the overpack from corrosion depends on the pH maintained in the buffer. At a pH < 10, a passive film on the steel surface is no longer stable and the concrete buffer can no longer impede corrosion. The pH of the cement buffer pore water reduces with increasing temperature. A maximum of 75 °C has been proposed for the interface with the overpack [Kursten, 2015] and an increment of 50 °C over the ambient temperature at 500 m depth [23 °C] almost approaches this value. The thermal evolution of the EBS has thus been calculated for vitrified waste in OPERA, assuming a pre-disposal cooling period of 100 years. The Belgian EBS design and material properties have been assumed. Figure 6-3-4 shows the calculated temperature increments at various points in the EBS.

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As the anaerobic period continues, out beyond the thermal period, after about 2000 years the chloride concentration at the overpack surface has been calculated to be equal to that of seawater. In this period, results from the EC CaST project suggest that, under OPERA expected conditions, the corrosion rate of carbon steel is independent of the chloride concentration [Swanton, 2015: p.51]. In addition, no increase in the anaerobic corrosion rate of carbon steel has been observed in the presence of sulphur species that might enter via Boom Clay pore waters [Smart, 2014], even were the buffer to degrade so that transport of such species were enhanced. The literature research in CaST indicates that aggressive corrosion species have no impact on the corrosion rates. Consequently, a uniform corrosion rate may be assumed in Period 3.

Even using generally conservative assumptions (such as an infinite dilution boundary at the liner-clay interface and no impact of pore clogging by precipitation of minerals) Kursten et al. (2015) calculate that alkaline conditions at the overpack/cement interface will last at least 80,000 years and the oxidative protective film that minimizes corrosion will be preserved over this period.

Degradation of the buffer cement could result in an increase in its porosity and a decrease of compressive strength. The mean compressive strength of the concrete buffer of RPC concrete is 47 N mm⁻², which is sufficient to preserve the mechanical integrity of the supercontainer at disposal depth. Owing to the slow degradation rate, no reduction in compressive strength is expected in the first 1000 years, so early mechanical failure of the overpack also appears unlikely.
Four cases for the longevity of the supercontainer overpack have been studied in OPERA:

1. Conservative case or early failure (EF): failure of the overpack after 1000 years (the OPERA performance target) [Rosca-Bocancea, 2017]. A 1000-year containment time would be provided by an overpack thickness of 3 cm.
2. Base case or default case (DV): failure of the overpack after 35,000 years [Rosca-Bocancea, 2017].
3. Realistic corrosion case or later failure (LF): failure of the overpack after 70,000 years. After about 80,000 years, it is conservatively assumed that there will be a step reduction in the pH of the concrete buffer, resulting in a faster corrosion rate, so no containment function is assigned to the overpack beyond this point [Rosca-Bocancea, 2017]. To achieve 70,000-year containment (i.e. prior to the change in corrosion rate) an overpack thickness of 4.4 cm would be required.
4. Optimistic case or late failure: failure of the overpack after 700,000 years [Schröder, 2017: NG7251].

Clearly, the thickness of the overpack can be optimised to meet specific longevity performance requirements that might arise from the OPERA assessment or future safety assessments. The thickness of the overpack is determined by the necessary thickness to sustain the mechanical and thermal stresses and an additional thickness for corrosion. This exercise has not been performed for carbon steel. In CORA, the thickness of a stainless steel lining in a disposal has been calculated to require a thickness of 3.0 mm to sustain the lithostatic pressure at 500 metre depth. There are two differences between the supercontainer overpack and the lining: the material i.e. carbon steel has a larger mechanical strength than stainless steel and the outer diameter of the lining is 6.1 cm [Barnichon, 2000]. i.e. larger than the carbon steel for vitrified HLW of about 50 cm but smaller than the outer diameter for the overpack for SRIF of about 90 cm. Assuming the oxygen available in the supercontainer for corrosion of the overpack being oxygen entrapped during fabrication: the maximum in iron-oxide thickness would be 0.05 mm. Consequently, anaerobic corrosion rates are used to determine the additional thickness for corrosion. The maximum in anaerobic corrosion rate in alkaline media for carbon steel is 0.2 µm/year [Kursten, 2015]. The additional thickness for corrosion for a period of 1000, 35,000, 70,000 and 700,000 years would be 0.2, 7, 14 and 140 mm. Assuming the thickness 30 mm to be a correct value to sustain the mechanical and thermal stress for a carbon steel overpack in the supercontainer, the thicknesses for these four periods become 3.0, 3.7, 4.4 and 17 cm.

In OPERA, in order to calculate the release rate of radionuclides from the EBS into the Boom Clay, it is conservatively assumed that all radionuclides are in solution and distributed in uniform concentrations within each of the EBS components. This allows estimation of the radionuclide concentration at the interface between the concrete liner and the Boom Clay and diffusion from the EBS into the clay to be calculated (see Chapter 8). Each EBS component is assigned a ‘dissolution volume’, which is its time-unvarying porosity, as a proportion of the total dissolution volume of the EBS. The contribution of the concrete buffer to the dissolution volume is 0.15 [Schröder, 2017: NG7251].

OPERA assumes no containment function for the inner, stainless steel CSD and EON canisters, once the overpack is breached. This is a conservative approach, which assumes that any void space in the canisters will allow them to collapse and rupture when lithostatic load is applied to them after weakening of the liner and overpack. Again, conservatively, it is assumed that all canisters would behave in this way.

Except for vitrified waste, radionuclides are conservatively assumed to be released instantaneously into the EBS porewaters after loss of the integrity of the overpack occurs: the so-called ‘failure time’ used in the safety assessment.

6.2.1.2 Uncertainties and further work

It is uncertain whether crack formation in the concrete buffer has an impact on the period of alkaline anaerobic conditions and the role of gases produced in the EBS has not been evaluated in OPERA. Although corrosion is understood in sufficient detail to support the use of the supercontainer, OPERA has not modelled the impacts on the EBS and the overpack of the well-known process of hydrogen gas formation by anaerobic corrosion. The potential build-up of corrosion gases in the EBS needs to be addressed in future assessments. Corrosion induced cracking in the concrete buffer initiated by build-up of hydrogen gas has been identified as one of the mechanisms that cannot be ruled out. A fluid-mechanics analysis could be used to investigate the tensile strength of degraded concrete.

The choice of cement formulation for the buffer is flexible. For example, appropriate compositions could prevent degradation resulting in the formation of expansive cracks by delayed ettringite formation. Also, as the Boom Clay pore water is expected to have a sulphate concentration comparable to or higher than seawater, use of a certified sulphate-resistant Portland cement might be considered.

As noted above, there is scope to optimise both the overpack and buffer thicknesses to provide sufficient radiological protection whilst preserving mechanical integrity of the supercontainer in the initial post-closure phase.

6.2.2 The Konrad Type II Container for depleted uranium

Depleted uranium is stored as $\text{U}_3\text{O}_8$ in a particle size range up to 4 mm in DV-70 containers. The open volume between the particles is too large for disposal and the containers themselves are not suitable for disposal. In OPERA, the $\text{U}_3\text{O}_8$ particles form the aggregate for a sulphate resistant, Portland cement-based concrete waste form, which is emphasised in standardised 4.6 m³ Konrad containers, which have a weight of up to 20,000 kg. To reduce the weight, limestone is used as part of the aggregate. This also provides calcium, but traces of $\text{U}_3\text{O}_8$ present in the stored $\text{U}_3\text{O}_8$ - Figure 6-3-5 shows the schematics of the disposal container and conditioning matrix.

The cement matrix for depleted uranium is similar to that used in the supercontainer buffer [Verhoef, 2014c] and the slow processes in the degradation of the cement matrix in the normal evolution scenario are also expected to be similar. Plasticisers are added to the cement in order to reduce the water-cement ratio, which permits easier emplacement and also reduces the permeability of the concrete.
Limitation of radionuclide release is provided by a low glass matrix dissolution rate in the geochemical conditions in the GDF (chemical durability) and the formation of a protective layer, which further limits dissolution. Archaeological artefacts illustrating the low rates of glass alteration are available (see Box 6-1). As the glass is brittle, it can contain or develop cracks, and the surface area exposed to porewaters depends on a ‘cracking factor’. Three values of cracking factors can be considered:

1. no cracking factor;
2. a cracking factor of 40: i.e. a distance of about 11 mm between cracks;
3. the same maximum reactive surface area as spent research reactor fuel (equivalent to a cracking factor of 5.8).

The Young’s modulus of the glass is about twice that of high-strength concrete, so the glass is expected to sustain the lithostatic load at disposal depth. Formation of cracks in the post-closure phase is not taken into account because experiments show that self-irradiation diminishes the glass density slightly and its mechanical properties appreciably improve, especially its resistance to cracking [Ribet, 2009]. Active glass might thus not have fractures at all, hence the inclusion of the ‘low’ case.

A cracking factor of 40 is determined from interpretation of experimental results with inactive glass on a full scale over the short-term range cooling during solidification of the vitrified waste. A cracking factor of 40 is the maximum elicited by experts in the Belgian programme [Ferrand, 2011]. The third assumption allows comparison of the radionuclide release from vitrified waste with that of spent research reactor fuel. The geometric surface area of spent research reactor fuel is equal to a ‘cracking factor’ of 5.8, which is close to the minimum elicited by experts in the Belgian programme.

In the OPERA safety assessment, the same maximum reactive surface area as spent research reactor fuel has been used.

6.3.1 OPERA assumptions for the behaviour of the vHfW matrix

The glass surface is altered by interaction with porewaters, which causes gel (dehydroxylation) or precipitation of secondary phases. Element-specific radionuclide release needs to be assessed if the formation of the altered layer is included in the modelling. As this information is not available for deep Boom Clay porewater conditions, congruent dissolution is used in OPERA in order to be able to assume non-chemical specific radionuclide release. This is a conservative assumption.

As with the steel of the overpack, glass corrosion rate depends on pH. Deissmann [2016a] evaluated the behaviour of the glass matrix over a pH range from 13.5 to 11.5. In OPERA, the overpack containment times are assumed to be larger than or equal to 1000 years, and a pH larger than 12.5 is not expected after this time. Similarly, based on the work by Kursten [2015], a pH as low as 11.5 is not expected in the first 80,000 years. Based on these pH values, OPERA uses a glass matrix surface dissolution rate of 0.006 g m⁻² day⁻¹ [Deissmann, 2016a]. Radionuclides are assumed to be released congruently, as a function of the dissolution rate after the failure time of the carbon steel overpack. The fractional dissolution rate for the same reactive surface area as spent research reactor fuel is 5.2×10⁻⁸ a⁻¹ [Schröder, 2017b: p.19-21]. In the assessment, the glass dissolution rates at a pH of 13.5 and 11.5 are used, and other cracking factors. The vitrified waste is assumed to dissolve either almost instantaneously, within 260 years (3.8×10⁻⁹ a⁻¹ fractional dissolution rate), or at a more realistic and slower rate, taking more than 6 million years to dissolve completely (1.6×10⁻¹⁰ a⁻¹ fractional dissolution rate) [Schröder, 2017, NRG1732/746: p.22]. A time-independent porosity of the glass waste form of 0.05 is assumed [Schröder, 2017: NRG1725: p.17].

6.3.1.2 Uncertainties and further work

The maximum cracking factor excludes the formation of an alteration layer. The French research project VESTALE is developing long-term behaviour models for vitrified waste packages. The GRAAL model (Glass Reactivity with Allowance for the Alteration Layer) will assess the impact of this alteration layer [Ribet, 2009]. The representativeness of current data and models under the more seawater-alkaline conditions expected in the deep Boom Clay of Netherlands needs to be further evaluated with respect to the cracking factor.

Nevertheless, current models of glass dissolution and radionuclide release used in OPERA are considered adequately conservative and it can be noted that the longevity of the glass is certainly greater than the ‘cross-over time’ of a few thousand years with respect to natural radioactivity, discussed in Box 2-1. In this respect, even a rapidly degrading glass matrix that is totally dissolved within a few thousand years will have exceeded its expected safety function. Indeed, the expected lifetime of the overpack, before water can access the glass, is already longer than this period.

6.3.2 Spent fuel from research reactors

Until 1996, spent research reactor fuel was sent back to the USA, but since 1996, storing in the Netherlands has been the preferred option. Three research reactors produce, or have produced, spent fuel for storage at COVRA [IAE, 2014: p.65], comprising both Highly Enriched Uranium (HEU: 93% 235U) and Low Enriched Uranium (LEU: 19.75% 235U). The fuel consists of 40 to 150 µm particles of uranium-aluminide (UAlx for HEU) or uranium-silicide (U3Si2 for LEU) dispersed in an aluminium matrix, bonded to aluminium cladding [Deissmann, 2016a]. The fuel is arranged in plates with a thickness of 0.51 mm for HEU and 0.76 mm for LEU [Verhoef, 2016, as shown in Figure 6-3-7].

The degradation behaviour of spent fuel once in contact with water is controlled by the corrosion behaviour of the aluminium matrix and cladding. Aluminium is a reactive metal that it is not thermodynamically stable in water and its corrosion rate depends on pH. Between pH 4 and 9, a protective oxide and hydroxide film passivates the surface and reduces corrosion, but the alkaline conditions of the supercontainer and GDF near-field facilitate the dissolution of aluminium and its alloys. Deissmann [2016b] gives a best estimate corrosion rate of 1 mm/a, which can be used to determine the hydrogen generation rate. In OPERA, an instant release of radionuclides after containment failure is assumed, without generation of gas.

OPERA has collected available corrosion rate data from papers published between 1998 and 2015 and the corrosion behaviour of the UAlx dissolution rate under alkaline, anoxic conditions has been assessed [Deissmann, 2016b]. The corrosion rate at pH=11 ranges from 1422 to 1524 µm per year at 25°C for unirradiated UAl.

No published corrosion measurements have been found for irradiated UAlx under anoxic, highly alkaline and saline conditions.

No data are available on the corrosion behaviour of U3Si2 (LEU) under anoxic conditions representative for the highly, alkaline, cementitious near-field environment [Deissmann, 2016b: p.31], so OPERA uses the same corrosion rates as for UAlx HEU. The corrosion of aluminium also produces significant quantities of hydrogen, generating substantially more hydrogen gas than the corrosion of the steel overpack in the supercontainer (see Box 6-2: Gas).
Dissolution of the cementsitious phase of the blast furnace slag concrete in the ECN canisters will be limited, because the pore water penetrating the overpack already has a pH of 12.5 during the long period in which portlandite in the concrete buffer of the super-container reacts with Bloom Clay pore waters. The EU research project 'Cebana', has investigated concrete made by COVRA for cladding geometries to be used in alkaline environments. In pH 10–12 m s⁻¹ [Verhoef, 2014c], sufficient to prevent instantaneous radionuclide release. OPERA has collected experimental data on organic degradation products relevant to these wastes [Wouters, 2016]. Their transport in Bloom Clay is likely be limited to dissolved organic carbon complexes [Wouters, 2016].

6.3.5 Low and Intermediate Level (LILW) waste forms

The largest LILW family by volume is depleted uranium, generated by UREXO. The UREXO enrichment process. The tailings that remain are potentially available for re-enrichment, so not normally considered as waste. If re-enrichment is not economically feasible, the tails are converted to solid uranium oxide (U₃O₈) in France and stored at COVRA. For disposal, depleted uranium particles will be conditioned in a matrix. As discussed in Section 3.2.2, the U₃O₈ particles form the aggregate for a sulphate resistant, Portland cement-based concrete waste form, which is emplaced in standardised 4.6 m³ concrete containers.

The second largest waste family by volume is compressed waste collected from some two hundred organisations, from nuclear power plants and research establishments to numerous types of industry and hospitals. The compressed waste includes materials from dismantling of nuclear and other installations and is mainly contained in highly alkaline waste streams. The organic material is processed by mixing the liquid waste and the solids used for vitrification, which are welded closed (see Figure 6–3–8). There is about 20% void space in the canisters.

The waste form contains radionuclides of two different sources: contamination from the fuel and activation products. Radionuclides from fuel contamination are assumed to be present on the surfaces of metal fragments, except caesium and iodine, which can diffuse into the cladding [Gagini, 1985; Inoue, 1987]. Activation products in the fuel cladding and other metal parts are assumed to be homogeneously distributed in the metals and their release rate into porewaters will be controlled by the corrosion rate of (predominantly) the fuel cladding. The corrosion resistance of the supercontainer overpack by corrosion. In reality it is expected that the concrete matrix in the ECN containers will limit water access to the wastes after overpack perforation, as well as adding further to the chemical conditioning provided by the other cementitious materials in the EBS.

The potential for criticality within a supercontainer holding two ECN containers of spent fuel needs to be further evaluated. Disposal of a single ECN canister in each supercontainer would reduce the possibility of criticality but may not be sufficient. In the previous research programme CORA, it was suggested to dispose of smaller waste canisters i.e. with an inner diameter of 13 cm [Dodd, 2000; p.44] instead of 74 cm as suggested in OPERA.

The potential build-up of corrosion gases should be evaluated in future assessments, as this could lead to gas transport of radionuclides in the Boom Clay. To avoid this, the possibility of having spent research reactor fuel reprocessed could be explored (to produce HLW), which also removes any potential for criticality.

COVRA also stores uranium filters from the production of medical isotopes from irradiated HEU targets. As with spent fuel, these will be packaged for disposal in ECN containers. These are assumed to have the same characteristics as spent research reactor fuel and, considering the relatively small number of packages expected, uranium collection filters have not been considered in the inventory for the calculation of the source term within OPERA. The current assumption that the uranium collection filters having the same characteristics as spent research reactor fuel is expected to be conservative.

6.3.3.1 OPERA assumptions for the behaviour of technological wastes

All radionuclides are conservatively assumed to be released instantaneously when the carbon steel overpack is perforated by corrosion. In the assessment, C-14 migration is assumed to be in the form of HCO⁻.

In reality, radionuclides produced by neutron activation of the fuel cladding would be released as a function of Zircaloy corrosion rate in pore waters in the EBS. In the pH range between 3.5 and 12.5, zirconium is passivated by ZrO₂ and the cladding will corrode extremely slowly. The susceptibility of Zr alloys to pitting corrosion by chloride ions also decreases in alkaline waters. In cementitious environments, pitting corrosion can be considered unlikely. After a few years of exposure to porewaters in alkaline environments, a uniform corrosion rate of around 1 mm year⁻¹ is expected to be established [Gras, 2014]. Assumption of instantaneous release is this conservative.

Hydrogen is formed by corrosion of Zircaloy, but the amount generated is less than that generated by corrosion of the carbon steel overpack in the supercontainer. As discussed previously, gas generation has not been considered within OPERA (see Box: Gas).

6.3.3.2 Uncertainties and further work

The EU CaST research project on the C-14 source term aims to reduce uncertainties in the mechanisms of C-14 mobilisation.

Exclusion of the formation of gaseous radionuclide species in the OPERA assessment affects the evaluation of C-14 impacts and future work should include the impact of corrosion gases in the potential formation of gaseous radionuclide species.

6.3.4 Other high-level wastes

Waste resulting from four decades of nuclear research exists as fuel assemblies that have been cut off from the spent fuel, then rinsed and dried. A canister of about 170 litres internal volume is filled with either hulls or end pieces. The hulls are made of zircaloy; other metal parts are usually made of inconel. End pieces are solid stainless steel sections. Drums with other waste arising from reprocessing fuels, such as pumps, stirrers and filters, are primarily made of stainless steel. All drums are compacted to produce pucks that are loaded into CSD-c canisters with similar outer dimensions to those used for vitrified waste, which are welded closed (see Figure 6–3–8). There is about 20% void space in the canisters.

The waste form contains radionuclides of two different sources: contamination from the fuel and activation products. Radionuclides from fuel contamination are assumed to be present on the surfaces of metal fragments, except caesium and iodine, which can diffuse into the cladding [Gagini, 1985; Inoue, 1987]. Activation products in the fuel cladding and other metal parts are assumed to be homogeneously distributed in the metals and their release rate into porewaters will be controlled by the corrosion rate of (predominantly) the fuel cladding. The corrosion resistance of the supercontainer overpack by corrosion. In reality it is expected that the concrete matrix in the ECN containers will limit water access to the wastes after overpack perforation, as well as adding further to the chemical conditioning provided by the other cementitious materials in the EBS.

OPERA has studied some aspects of the behaviour of these wastes, but makes conservative assumptions in the assessment: all radionuclides are assumed to be released instantly upon perforation of the supercontainer overpack by corrosion. In reality it is expected that the concrete matrix in the ECN containers will limit water access to the wastes after overpack perforation, as well as adding further to the chemical conditioning provided by the other cementitious materials in the EBS.
6.3.5.1 OPERA assumptions for the behaviour of cemented LLW

Although the cementitious materials provide both chemical and physical containment, the OPERA safety assessment assumes instantaneous release of radionuclides upon failure of the outer containers. As discussed in section 5.3.2.3, this is conservatively assumed to occur immediately upon closure of the GDF. The waste form and packings are assumed to contribute to a dissolution volume, with a time-independent porosity of 0.15, as discussed earlier [Schröder, 2017: NRG7251, p.17]

6.3.5.2 Uncertainties and further work

Organic matter in compacted waste and spent ion exchangers may act as a nutrient for microbial activity in the period after placement of the wastes. It is uncertain what the microbial activity of this emplaced LLW waste will be. The EU research project ‘Microbes In Nuclear waste Disposal (MIND)’ is investigating potential microbial degradation of the waste form.

6.4 The radioactivity of the wastes

The bulk of the radioactivity in the wastes is contained within the HLW, with the vitrified HLW in the CSD-v containers dominating the inventory. However, as will be seen in Section 8, it is only these radionuclides that contribute most to the passive isolation of the vitrified HLW in situ, within the waste materials, within a few hundreds to a few thousand years after disposal.

Even though the contribution to the total activity of the long-lived radionuclides is considerably smaller than the short-lived radionuclides for most waste groups (see Appendix 5 for the complete inventory), they must be taken into account in the safety assessment and, as will be seen in Section II, it is only these radionuclides that give rise to the small radiological impacts of the GDF in the far future.

Table 6-3-1: Anticipated overall radioactivity of each waste group in the OPERA disposal concept and the main contributing radionuclides at the time of disposal (2130) for each of the waste groups discussed in Section 6.3 and identifies those radionuclides that contribute most to the total activity of each group.

<table>
<thead>
<tr>
<th>Activity per waste family or aggregated waste family (Bq)</th>
<th>% of total activity in 2130</th>
<th>The three most radionuclides contributing most to the activity in 2130</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSD-v</td>
<td>3.37E+17</td>
<td>88.7</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Sr-90</td>
<td>Am-241</td>
<td></td>
</tr>
<tr>
<td>Cs-137</td>
<td>Sr-90</td>
<td></td>
</tr>
<tr>
<td>Sr-90</td>
<td>Cs-137</td>
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<tr>
<td>Cs-137</td>
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Box 6-1: Analogies from Nature and Archaeology

Since the earliest studies on geological disposal it has been recognised that rock formations hold much natural evidence for the containment and isolation capacity of the geosphere – indeed, this is the basis for identifying geological disposal as the most appropriate means of managing long-lived radioactive wastes. All of the processes with which this safety case is concerned have been active over millions of years in deep rock formations. Studies of geological settings similar to that of the GDF can provide confidence that we understand the nature, scale and rate of processes such as chemical diffusion, water movement in clay formations, the movement of natural radionuclides and the response of clays to thermal and mechanical loads [Miller et al., 2006]. Particularly useful research objects have been uranium and other ore bodies, and Neogene clay formations similar to the Boom Clay. One striking example of the former is the Cigar Lake uranium deposit in Canada, this is located in sandstones at a similar depth to a GDF and is surrounded by a natural envelope of clay minerals, which has isolated the behaviour of man-made materials under conditions similar to those in the engineered barrier system. Artefacts discovered in saturated, anaerobic soils with no through-flow of water – conditions equivalent to those in the EBS after the GDF is closed – show that the material degradation can occur. Of particular interest in the OPERA safety case is the corrosion rate of the steel overpack of the supercontainer. Almost a million iron nails and other objects with a total mass of about 7 tonnes were buried some time around 87 AD, under 3 metres of soil in a shallow pit at the Roman fortress of Inchtuthil, in Scotland (Pitts and St. Joseph, 1985). The nails were discovered in 1953 – and those in the centre of the deposit are exceptionally well preserved, showing the slow pace of anaerobic corrosion, even close to the ground surface on a river floodplain, over a period of almost 2000 years.

Stagnant, anaerobic environments in muds and clays provide exceptional preservation for other, much more fragile archaeological materials. Roman wooden writing tablets (with the writing still legible) have been found at two sites in the UK (Vindolanda and Londinium; e.g. http://www.vindolanda.cas.ac.uk/) and a wide range of items, from leather sandals to the wooden and iron mechanism of a complex Roman water wheel (including the buckets) have emerged in recent excavations under central London.

Roman buildings also show the potential longevity of concrete, an issue with which OPERA is also concerned. Although of different composition to those being evaluated in OPERA, many Roman cements and concretes continue to maintain their function and stability after almost 2000 years of exposure to the atmosphere or to wet soil conditions. At Hadrian’s Wall in northern England, surviving Roman cements still contain the C-S-H compounds that characterise modern Portland cements [Miller et al., 2000]. Perhaps the best-known example is the unreinforced concrete dome of the Pantheon in Rome. Built about 120 AD, this was the largest self-supporting roof structure in the world and the largest dome until the 19th Century. It still carries the load-bearing structure today, despite being almost 2000 years old. Examples such as these give confidence in both the mechanical stability of the unreinforced tunnel liner and backfill in the OPERA GDF, and along with geological analogues of cement-like materials, the longevity of the cementitious engineered barrier system itself.
Gas can be generated in the wastes and the materials of the EBS by:
1. Alpha decay of radionuclides, leading to helium production;
2. Radiolysis of porewaters, leading to hydrogen and oxygen production;
3. Microbial degradation of organic materials, generating CO₂ and CH₄, possibly including small quantities of radioactive gases, in particular C-14;
4. Anoxic corrosion of metals in the waste and the containment diffusion of hydrogen and is the principal gas source in a closed GDF.

For the wastes and packages in the OPERA GDF, the first two of these processes lead to negligible gas generation, and thus have no impact on radionuclide movement away from the GDF.

For the third mechanism, a viable microbe population is required in the EBS for microbial degradation to occur. However, the viable microbial size is 0.2 µm to 2 µm, which is larger than the 10-50 pm pore throat size in undisturbed Boom Clay (Wouters, 2016) or the even smaller pore throat size of intact concrete. Microbial activity in both the near-field Boom Clay and the concretes of the EBS is therefore expected to be limited due to space restrictions, and those microbes present are expected to remain in a dormant mode. Even if microbes are active, experiments with Boom Clay have shown that methanogenic bacteria can convert the hydrogen generated by anaerobic corrosion of metal to methane, which would reduce the volume of free gas produced by a factor of four, thus reducing the probability of gas pressure build up.

Anaerobic corrosion of metals in the waste packages and waste form is expected to be the main mechanism by which gas is produced. The reaction involves iron and steel, which is the primary component of the waste containers. The reaction can be summarized as follows: Fe + H₂O + CO₂ → Fe(OH)₂ + CO₂. The reaction is exothermic and produces hydrogen gas, which can dissolve in the pore water and form hydrogen bubbles. The hydrogen gas can then escape from the system, leading to an increase in gas pressure.

Dispersion rates have been calculated for the first process, for anaerobic corrosion of iron and steel, assuming a linear (1-D) disassociation from the EBS into the Boom Clay, and a reactive metal surface area of 10 m²/m³. In the model, free gas is released from the geosphere at a rate of 2-10⁻³ m³/m²/year.

In the OPERA disposal concept, 1 CSD or 2 ECN containers are proposed for each supercontainer. The external surface areas of the carbon steel overpacks are 10 m², and the reactive surface area is estimated to be 10 m² per ECN container.

The potential impacts of gases depend on the rate at which they can be dispersed. Dispersive mechanisms (see illustration for clay below: Wiseall, 2015):
1. Advection and diffusion of dissolved gas in pore waters in the EBS and Boom Clay;
2. Visco-capillary flow of gas and water (two-phase flow) in the pore structure of the EBS and Boom Clay;
3. Dissolvent controlled gas flow (porosity dilation, possibly leading to micro-fracturing);
4. Transport of gas generated in micro-fractures, which might occur if the previous three mechanisms are unable to dissipate gases into the geosphere, such that the gas pressure exceeds the sum of the principal stresses and the tensile strength.

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In assessing the overall behaviour of gases in the GDF system, their transport in the EBS also needs to be considered. The transport of gas is high in the foamed concrete tunnel fill, which is a beneficial property in the post-closure phase as it can facilitate the free gas to leave the system. Limiting the build-up of gas, corrosion-induced cracking in the concrete buffer initiated by build-up hydrogen gas has been identified as a mechanism that cannot be ruled out.
7. Evolution of the GDF system

Our understanding of the properties and behaviour of the natural and engineered barrier systems underlies the concept of isolation and containment provided by geological disposal. Safety assessment, as presented in detail in Chapter 8, quantifies this behaviour in order to forecast the performance of each component of the system and of the whole multibarrier system.

The information to quantify performance is variable and contains different types and levels of uncertainty. Safety assessment allows for this by making conservative simplifications, assuming poor performance, using pessimistic parameter values and omitting potentially beneficial processes if they are not well-enough quantified. The results of safety assessments are thus designed to be conservative, in that it is expected that they will make pessimistic forecasts of system performance. Nevertheless, it is essential 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 to be taken between realism (somewhere close to expected behaviour) and simply showing the system is safe, even acknowledging the uncertainties along the way. This allows a balanced view to be taken between realism (somewhere close to expected behaviour) and simply showing the system is safe, even acknowledging the uncertainties along the way.

7.1 Closure to 1000 years

7.1.1 Expected behaviour

When a disposal tunnel is closed and sealed there will be very little void space in the EBS. All large open spaces in the tunnel and in the supercontainer will be filled with cementitious backfill or grout. The voids will consist of the porosity of the cement and concrete components, which will be partially filled with water from the casting of the materials. The remaining porosity will contain air. Oxygen in the air will diffuse through the concrete and, within a few years, will be consumed by reaction with the supercontainer outer steel shell and the inner steel overpack, as well as other components of the disposal system.

In the early stage after closure, a hydraulic gradient will exist from the high hydrostatic pore pressures in the Boom Clay, across the liner and into the tunnel backfill, allowing water to move into the unsaturated porosity of the EBS. As a result, any void porosity in the tunnel will progressively become saturated with pore water from the surrounding Boom Clay, possibly within several decades and, eventually, all sections of the tunnels outside the supercontainer shell and other waste containers will be saturated with pore water. Over the first decades to a few hundred years, there will also be a temperature gradient outwards into the Boom Clay, as the radioactive decay heat of the spent fuel builds up the temperature, then declines. This thermal gradient away from heat-emitting waste supercontainers will partly counteract the hydraulic gradient and will tend to prevent saturation in the early decades after closure. When these processes have balanced and in situ hydraulic conditions have been re-established, hydraulic gradients will have dissipated and all the pore waters in the clay and EBS will be connected and stagnant, with no further movement of water.

The elevated temperature and the influx of clay pore waters containing dissolved organic carbon (DOC) and other solutes will promote chemical reactions leading to the localised precipitation of minerals, for example between tunnel liner blocks and in the pore spaces of concrete. There will also be direct chemical interaction between the high alkalinity pore fluids in the liner, with components such as calcium hydroxide diffusing out into the pore waters and minerals of the Boom Clay, creating a narrow (some centimetres) reaction zones into the clay.

The lithostatic load of the geological formations overlying the tunnels will be taken up by the tunnel liner, which has a design and thickness calculated to absorb the load without deformation and decades and, eventually, all sections of the tunnels outside the supercontainer shell and other waste containers will be saturated with pore water. Over the first decades to a few hundred years, there will also be a temperature gradient outwards into the Boom Clay, as the radioactive decay heat of the spent fuel builds up the temperature, then declines. This thermal gradient away from heat-emitting waste supercontainers will partly counteract the hydraulic gradient and will tend to prevent saturation in the early decades after closure. When these processes have balanced and in situ hydraulic conditions have been re-established, hydraulic gradients will have dissipated and all the pore waters in the clay and EBS will be connected and stagnant, with no further movement of water.

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The elevated temperature and the influx of clay pore waters containing dissolved organic carbon (DOC) and other solutes will promote chemical reactions leading to the localised precipitation of minerals, for example between tunnel liner blocks and in the pore spaces of concrete. There will also be direct chemical interaction between the high alkalinity pore fluids in theliner, with components such as calcium hydroxide diffusing out into the pore waters and minerals of the Boom Clay, creating a narrow (some centimetres) reaction zones into the clay.

The lithostatic load of the geological formations overlying the tunnels will be taken up by the tunnel liner, which has a design and thickness calculated to absorb the load without deformation and without transmitting stresses through to the rest of the EBS. The shape of the stress field at 500 m in the Boom Clay is not known at present and will need to be established by field measurements at depth in the future. It might be expected to vary from location to location in the Netherlands and is likely to be anisotropic, rather than the liner being subject to equal stresses all round.

The concrete is expected to degrade slowly by reaction with clay pore waters, as calcium and other components diffuse out and into the clay and some of the cement phases begin to transform. This process will occur from the Boom Clay / tunnel liner interface and will be slow, penetrating only a few tens of millimetres into the liner after 1000 years (Seetharam, 2015: p.11). As a result of decalcification, the liner could begin to lose some of its compressive strength towards the end of the first 1000 years and some of the anisotropic lithostatic load might begin to be transmitted through the liner and onto the tunnel backfill and the supercontainer, although this seems unlikely, given the expected small depth of penetration of decalcification into the liner. By the end of this period, the thin outer supercontainer steel shell is expected to have corroded sufficiently that it offers little or no resistance to load, so any load would be taken up by the buffer concrete and then the overpack.

The alkaline (high pH) conditions in the concrete liner, backfill and supercontainer buffer will persist throughout this period, limiting
Clay, as the radioactive decay heat of the spent fuel builds up the temperature, then declines. This thermal gradient away from heat-emitting waste containers will partly counteract the hydraulic gradient and will tend to prevent saturation in the early decades after closure. When these processes have balanced and in situ hydraulic conditions at the repository, the hydraulic gradient will have dissipated and all the pore waters in the clay and EBs will be connected and stagnant, with no further movement of water.

The elevated temperature and the influx of clay pore waters containing dissolved organic carbon (DOC) and other solutes will promote chemical reactions leading to the localised precipitation of minerals, for example between tunnel liner blocks and in the pore spaces of concrete. There will also be direct chemical interaction between the high alkalinity pore fluids in the liner, with components such as calcium hydroxide diffusing out into the pore waters and mineral grains of the Boom Clay forming a narrow (some centimetres) reaction zones into the clay.

The lithostatic load of the geological formations overlying the tunnels will be taken up by the tunnel liner, which has a design and thickness calculated to absorb the load without deformation and without causing stresses through to the EBs. The shape of the stress field at 500 m in the Boom Clay is not known at present and will need to be established by field measurements at depth in the future. It might be expected to vary from location to location in the Netherlands and is likely to be anisotropic, rather than the liner being subject to equal stresses all round.

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The alkaline (high pH) conditions in the concrete liner, backfill and supercontainer buffer will persist throughout this period, limiting the amount of corrosion of the inner steel liner and the overpack core in water under anaerobic conditions, hydrogen gas will be generated and will diffuse out of the EBs and into the Boom Clay, which will be anoxic.

At the end of this period, it is expected that the properties and geometry of the tunnels are unlikely to change significantly. 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 spent fuel will have cooled substantially and will not have come into contact with water. The same behaviour is expected for the utilised HLW supercontainers. For the non-radiological materials, their initially high radioactivity will have reduced considerably during this period of total containment in the supercontainer (see Box 2–1).

Elsewhere in the GDF, the ILW and LLW steel packages will start to corrode, possibly losing their integrity, allowing waste to begin to leak slowly.

7.1.2 Conditions assumed in the safety assessment

All variants evaluated in the safety assessment assume that the supercontainer overpack contains all the radionuclides for 1000 years (while the ILW containers are ‘failed’ from the time of GDF closure). The supercontainer ‘early failure’ base case evaluation assumes that the overpack remains intact throughout but that the outer canister can be breached to allow waste to begin to escape from the waste container. For both these high hazard potential wastes, their radionuclides will have cooled substantially and will not have come into contact with Boom Clay. For this period, the supercontainers remain intact throughout this period (Seetharam, 2017, NES 725).

For ILW, 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 (TENORM), the containers are assumed to fail at 1000 years, with the subsequence release of uranium (and Th and Np) into the Boom Clay, assumed to be limited by its low solubility [Seetharam, 2017: OPERA-PIU-732/742].

7.2 1000 to 10,000 years

7.2.1 Expected behaviour

Between 1000 and 10,000 years the concrete components of the EBs are expected to undergo slow mineral transformation by decalcification and the dissolution of cementitious minerals, which could lead to some loss of strength of the tunnel liner. The porosity of the tunnel components could increase, but mineral precipitates (such as calcium carbonate) could also accumulate and block barren pore spaces with Boom Clay waters. The rate of all of these processes will be controlled by the slow process of inward and outward chemical diffusion in the stagnant pore waters in the EBs and Boom Clay.

By the end of this period, at about 1000 years, the liner and the backfill will have undergone 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, such that lithostatic load could now be applied to the overpack in some parts of the EBS. Because the clay at these locations (p.12, 13) in the buffer pore waters will still persist, the slow corrosion rate of the overpack steel would continue. Nevertheless, it is expected that all the supercontainers would retain their integrity throughout this period. Hydrogen gas will continue to be generated from anaerobic corrosion of the steel overpack and will diffuse out into the clay.

By 10,000 years, most of the short-lived radioactivity in the spent fuel 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 the (now reprocessed) fuel was originally manufactured.
The maximum rate of water movement would be in the order of 2 × 10^{-6} m/a. Compared to the rate of diffusion of dissolved materials, the advective flow is negligible [Grupa, 2017: NRG7111: p. 19].

Studies on the Opalinus Clay in Switzerland [OPA main Safety Report: Nagra, 2002; p. 204] are illustrative of the impact of slow diffusion combined with sorption on radionuclide movement through a clay formation. Many radionuclides diffuse so slowly with respect to their decay half-lives that they will decay to insignificance during transport through a thick clay formation. Poorly sorbing, long-lived anionic radionuclides such as Cl-36 (half-life c. 300,000 years), Se-79 (half-life c. 327,000 years) and I-129 (half-life of 1.6 million years) will eventually diffuse out of the clay and into the overlying formation over a time period similar to or in the case of very long-lived I-129, less than their half-lives, although a few hundreds of thousands of years are still required for full breakthrough. The more highly sorbing and long-lived radionuclides, as well as the low sorbing but shorter lived radionuclides, require a period that is about 100 times their half lives to diffuse across the clay, so will decay substantially. U-238 and Th-232 would take hundreds of millions of years or more to diffuse across the Opalinus Clay.

When the more mobile nuclides reach the aquifer system in the overlying sediments, migration to the biosphere can occur as a result of advective flow, although it should be noted that other clay layers might be present between the host Boom Clay and the aquifer, and this will further hinder radionuclide movement. It is expected that some radionuclides will be sorbed to the sediments during transport. Due to sorption, dispersion and the large delay and dilution in space and time, the mobile radionuclides can reach the biosphere only in extremely small concentrations. In addition, if the GDF is located below the transition to salt water (which is likely to be the case in many locations in the Netherlands), radionuclides will have to cross the salt water/fresh water interface before they can reach the biosphere.

After a million years, residual, immobile and long-lived radionuclides will remain within the degraded EBS. U-238, the main component of the depleted uranium TENORM waste, 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 just as any naturally occurring ore body.

7.4.2 Conditions assumed in the safety assessment

The 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 over this time period. The base case model assumes that radionuclides take about 30,000 years to reach the biosphere, once they have left the Boom Clay. The base case model makes the conservative assumption that none of the radionuclides is sorbed and retarded during transport through the overlying formations. These assumptions are not expected to change until a site selection process has started since the potential sorption in the overlying formations is site-specific.
8. The OPERA Safety Assessment

A central part of a Safety Case for a GDF is the modelling and calculation of potential impacts of the GDF on the environment for long times into the future. In this safety case, the function of the quantitative assessment is to provide as realistic a representation as possible of the long-term evolution of the GDF in order to optimize the disposal concept, steer the development of knowledge and guide research. It should also contribute to enhancing confidence in post-closure safety.

The safety assessment involves developing models of all significant processes and quantifying the necessary parameter values used to calculate the evolution of the geological disposal system as a function of time. This chapter first summarises briefly the linked models that are used to calculate the radioactive releases to the biosphere and potential impacts in terms of radiation doses to people. The results of the safety assessment calculations are presented and compared with certain yardsticks.

8.1 Modelling approach

The safety assessment model to calculate the movement of radionuclides in the geological disposal system and the potential health related effects as a function of time after disposal distinguishes four different compartments: the repository, the host rock, the overburden and the biosphere. Figure 8-1 shows the compartments used in modelling the transport of radionuclides from the EBS through to their uptake by people [Schröder, 2017: NRG7251]. The calculational models for each compartment are described in more detail in [NRG72712] (Boom Clay), [GRS72222] (Overburden), and [SCX613 & NRG7232] (Biosphere).

The model is a one-dimensional (1D) pathway through the different compartments. The movement of radionuclides through the geosphere considers diffusion in the clay and advective transport and dilution in the overburden. For substances with migration rates determined purely by advection, diffusion and linear sorption, 1D is sufficiently accurate. To properly handle the effect of solubility limitations in the Waste-EBS compartment, [Meessen, 2017: Annex OPERA-PUI-NRG7214] introduces a 1D approach with the capacity of a full two-dimensional (2D) method. This method is called ‘pseudo’ 2D and is included in the 1D PA model for migration of radionuclides in the Boom Clay.

B.1.1 Uncertainties in the Modelling

The safety case needs to consider different kinds of uncertainties, including uncertainties in parameter values, in the models, in the scenarios and in the disposal system [e.g. IAEA, 2012]. The effect of uncertainties propagates through the overall performance assessment.

- **System uncertainty.** This uncertainty arises from incomplete understanding or characterisation of the disposal system. In the present report, the uncertainties related to the performance of each individual component of the safety system are discussed in Chapters 5 and 6 immediately after the description of the expected behaviour.
- **Scenario uncertainty.** Uncertainty is introduced when the possible evolutions of the disposal system are described. The uncertainties depend on how well the features, events and processes of a scenario are understood. The scenarios and the expected evolution of the system are described in Chapters 4 and 7.
- **Model uncertainty.** The prime uncertainty here relates to whether the conceptual models sufficiently well describe the behaviour of (parts of) the disposal system. Reducing uncertainty involves literature searches, experimental evaluations in the laboratory or the field and the study of comparable archaeological and natural analogue systems. Further uncertainty may be introduced in the translation of the conceptual models into calculational models and their integration into a safety assessment model. This involves model simplifications that need to be well-argued and, preferably, tested for whether the calculational models correctly represent the conceptual understanding.
- **Parameter uncertainty.** The calculational and safety assessment models require values for all parameters and here numerical uncertainty can occur, for example related to the measurement technology and sampling methodology. Also, parameter uncertainty exists due to the variability and heterogeneity of natural materials. Of particular importance for the OPERA Safety Case is the fact that currently no GDF location is selected and, as a consequence, the safety assessment must consider a larger range of conditions. In OPERA, uncertainty ranges for Boom Clay properties were analysed and applied to calculate the effect of the parameter ranges on radio-nuclide migration.

Model and parameter uncertainties are considered quantitatively in many OPERA projects and also discussed in this Chapter. The preferred approach is to use realistic or best estimate data and assumptions where possible, with evaluation of the uncertainties in the results that this introduces. In practice, a combination of best estimates and conservative assumptions has been employed in order to avoid overprediction of achievable safety levels. The selection of input parameter ‘best estimate’ value, determining their ranges [OPERA-PUI-NRG7251] and the assessment of their effect on long-term safety can be found in [OPERA-PUI-GRS7312], [OPERA-PUI-NRG7331] and [OPERA-PUI-GRS732/746].

The numerical uncertainties are commonly dealt with by performing sensitivity analyses in which the relevant parameters are varied throughout their potential ranges. This can be done through deterministic modelling of multiple cases or by probabilistic models in which parameter distributions rather than specific values are employed [OPERA-PUI-GRS732]. In the probabilistic sensitivity analysis, parameter independence can be assumed, but preferably the correlation of parameters with each other should be taken into account in order to exclude physically unrealistic combinations. As yet in OPERA, mostly deterministic modelling has been employed [Schröder, 2017: NRG732/746].

B.1.2 Modelling the Waste-Engineered Barrier System

The waste-EBS compartment of the model is sub-divided into five sub-compartments, which contain the waste families described in Chapter 6.3, as shown in Figure B-2. For the assessment, the LLW families have been allocated to two disposal sections of the GDF: a depleted uranium section and an aggregated LILW disposal section.
8.1.4 Modelling the overlying and underlying geological formations

As described in Section 5.2, the formations surrounding the Boom Clay are predominantly highly permeable, sandy units, although there are some clay beds within them. Transport times of dissolved species from the top and bottom of the host rock to the surface water have been determined [Valstar, 2017] for potential evolutions of the surrounding formations. As transport times and retardation are site specific, conservatively the shortest transport time for a moderate climate and no retardation was assumed in the results presented here. In practice, for some species, retardation will result in longer transport times. Furthermore, the layered structure of the aquifer system has been modelled by one aquifer segment with averaged characteristics. Figure 8-4 shows the schematics of radionuclide transfer at the boundary between the Boom Clay and the overlying geological formations.

8.2 Treatment of the biosphere

The biosphere acts as the receptor for any radioactivity that moves upwards from the geosphere and the safety assessment needs to model biosphere processes that control how people might be exposed to radionuclides transported from the GDF. The calculated exposure in the biosphere depends on climate, biosphere type, and human behaviour. In the timeframe from 10^3 to 10^6 years after closure of the GDF (the period in which radioactivity may reach the biosphere), significant changes in climate, biospheres and human behaviour will occur. Consequently, for this time period, simplified (stylised) models are commonly used, including one or more reference biospheres based on temperate climate conditions [IAEA, 2003: p.28]. These models can make use of the information in databases on the environmental transfer of radionuclides in the biosphere [IAEA, 1999]. This is also the approach followed in the OPERA biosphere model. Three receptor interfaces between the biosphere and formations overlying the Boom Clay are treated in the model: well, surface water bodies (rivers, lakes, ponds) and wetland (soil). These are indicated in green in Figure 8-5. From these water bodies, potential radionuclide uptake can take place by ingestion, inhalation and external radiation. Ingestion can be direct, by drinking from the water well, or indirect, for example by eating meat from cattle that drank water from the well, or eating cereals irrigated with water from the well. Assuming that one of the three pathways is dominating, four subcases can be defined in which the inflow to the biosphere follows exclusively one of the three routes: drinking water well case, the irrigation water well case, the rivers or lakes case, and the wetland case.

Mechanistic model

As described in Section 5.1, in OPERA a schematic of radionuclide transfer at the boundary between the Boom Clay and the overlying geological formations. Figure 8-4 shows the schematics of radionuclide transfer at the host rock - overburden interface [Schröder, 2017: NRG6725].
In the safety assessment, the dose constraint and the radio toxicity concentration in biosphere water are used:

- **Dose constraint.** The International Committee on Radiation Protection (ICRP) recommends using an individual dose constraint of 0.3 mSv per year for a preliminary design-basis evolution with the most expected events [ICRP, 2013:p.14]. In the safety assessment for a GDF in the Netherlands, a value 0.1 mSv per year is used. The basis for this value is described in Section 3.1.

- **Radio toxicity concentration.** The radio toxicity concentration is compared with the required quality standards under the Dutch Water Framework Directive. In the safety assessment, the radio toxicity concentration of biosphere water is compared with the average annual environmental quality standard (AA-EQS) value for surface waters, extrapolated to the combined radio toxicity of natural uranium and its daughter radionuclides. The resulting reference value for radio toxicity in biosphere water is 8 Bq m⁻³. Although this value is lower than in regulations for drinking water, it is close to actual measured concentrations of uranium in Dutch topsoils [Hart, 2017].

### 8.3.2 Other yardsticks

Comparison to present-day measures of safety may be the simplest way to interpret the results of the safety assessment. However, these measures have been developed for the current climate, biosphere and human behaviour, which will change significantly during the life of a GDF. Therefore, estimated doses to the public can usefully be complemented by other yardsticks on post-closure performance of components of a GDF and/or by comparison with natural processes. An example is the fraction of the total radio toxicity in the different disposal system components, which provides understanding of how the principal barriers contribute to safety. Another example is the radio toxicity flux of radionuclides naturally present in the overburden to the biosphere.

### 8.3 Yardsticks for judging post-closure performance

#### 8.3.1 Calculated radiation doses

Calculated radiation doses indicate the levels of protection afforded by the disposal system and can be used to guide the optimisation of the disposal system. For interpretation of the calculated results the doses and concentrations are compared to present day measures of safety: reference values or yardsticks. In OPERA, different reference values have been developed [Hart, 2017].

#### 8.4 Safety assessment of the Normal Evolution Scenario

This section describes the main results of calculations for the Normal Evolution Scenario (NES). To represent as realistic a representation as possible of the long-term evolution of the GDF, the reference case of the NES uses ‘best estimate’ parameter values, provided the variability and uncertainty are considered to be reasonably quantified. There where is not a solid basis for setting a best estimate, ‘conservative’ (i.e., pessimistic) parameter values are used. A conservative value allocates, for example, low or zero effect to a beneficial containment property such as retardation in the surrounding formations.

In Chapters 5 and 6, best estimate values (median or default values, DV) for NES parameters are described as well as a number of parameter variations. These variations lead to a number of cases in the NES as shown in Table 8-4-1 [Rosca-Bocancea, 2017; Schröder, 2017: NRG732/746]. These cases together are presented as the reference case for the present stage of OPERA. Further work in future stages of OPERA will evaluate additional cases and scenarios.

#### B.4.1 Calculated radiation doses in the base case

Figure B-6 shows the base case for the NES (default parameter values) for a supercontainer and presents the calculated radiation doses to individuals as a function of time after GDF closure, for all the wastes in the GDF.

Figure B-7 shows the same calculation results, identifying the six radionuclides that contribute most to the outcome. Two radionuclides contribute almost all of the calculated peak exposure: about 90% of the exposure comes from Se-79 and I-129, which is predominantly from the SRRF and the non-heat generating HLW (CSD-1). Se-79 and I-129 are fission products, originally present in the wastes in the GDF.

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6. The dose constraint is a prospective, source-related restriction on the individual dose from a source that provides a basic level of protection for the most highly exposed individuals and serves as an upper bound on the dose in optimisation of protection for that source [ICRP, 2013:p.19]. The source, in this case, is the waste in the GDF.

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**Table B-4-1: Cases in the Normal Evolution Scenario considered in this report.**

<table>
<thead>
<tr>
<th>Component</th>
<th>Case</th>
<th>Subcases shown in this report</th>
<th>Parameter and their values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste-EBS</td>
<td>Supercontainer for HLW: containment failure</td>
<td>Failure base case (DV)</td>
<td>35,000 years</td>
</tr>
<tr>
<td></td>
<td>Early container failure (EF)</td>
<td>1,000 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Late container failure (LF)</td>
<td>70,000 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Late failure</td>
<td>700,000 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>vHLW: period for complete dissolution glass waste matrix (dissolution rate)</td>
<td>Release base case (DV)</td>
<td>20,000 (5.2×10⁻ⁱ a⁻¹)</td>
</tr>
<tr>
<td></td>
<td>Slow release case (SR)</td>
<td>6.25 million years (1.6×10⁻⁷ a⁻¹)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fast release case (FR)</td>
<td>260 years (5.2×10⁻⁷ a⁻¹)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solubility U, Th and Np in cementitious environment</td>
<td>Solubility case (DV)</td>
<td>e.g. U: 1×10⁻⁵ mol/l</td>
</tr>
<tr>
<td></td>
<td>Low solubility case (LS)</td>
<td>e.g. U: 1×10⁻⁷ mol/l</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Konrad container for depleted uranium</td>
<td>Failure base case (DV)</td>
<td>1,500 years</td>
</tr>
<tr>
<td></td>
<td>Early container failure (EF)</td>
<td>150 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Late container failure</td>
<td>200,000 years</td>
<td></td>
</tr>
<tr>
<td>Host rock</td>
<td>Pore diffusion coefficient</td>
<td>Median (SV)</td>
<td>e.g. I: 1.3×10⁻⁴ m²s⁻¹</td>
</tr>
<tr>
<td></td>
<td>Maximum (HR-1)</td>
<td>e.g. I: 1.6×10⁻⁴ m²s⁻¹</td>
<td></td>
</tr>
<tr>
<td>Overburden</td>
<td>Aquifer no retention of radionuclides</td>
<td>Travel time</td>
<td>3.7,700 years</td>
</tr>
<tr>
<td>Biosphere</td>
<td>Stylised biosphere</td>
<td>Dilution by dispersion</td>
<td>4.5</td>
</tr>
</tbody>
</table>
used fuel from the research and power reactors. 

![Diagram of supercontainer failure](image)

The peak calculated exposure occurs after the time an ice age is expected to have occurred. The other radionuclides that appear in the calculations of radiation dose (although contributing insignificantly) are K-40, which is conservatively set to 0 [NRG6123]. K-40 is a widespread radionuclide, naturally present in many rocks and minerals, as well as in the bones of the human skeleton. Its natural exposure dose is $1.65 \times 10^{-6}$ Sv per year [Bourgondiën, 2016], which exceeds the calculated contribution from LILW by more than a thousand times. Radiotoxicity concentration in biosphere water shows a similar profile, with the main contributions from the same radionuclides. Maximum concentration is about three times lower than reference value selected for biosphere waters.

### 8.4.2 Performance of the GDF system

The supercontainers hold the largest fraction of the radioactivity in the GDF and contain it completely until their allocated time of failure. In the NEs base case, at 3,500 years, all the super-containers are pessimistically assumed to fail together and most of the radioactivity in them to become instantly available and diffuse into the Boom Clay. From this time onwards, as shown by the green line in Figure 8.9, the bulk of the total radiotoxicity in the system resides in the Boom Clay.

![Graph showing effective dose rate over time](image)

### 8.5 Sensitivity analyses and opportunities to optimise the system

Optimising radiological protection is a goal in any GDF project. He required measures may raise the costs for disposal and their justification may need to be provided by calculating the sensitivity of the model to changes in the parameters of interest.
of the calculated doses to such measures: for example, having a less leachable waste form and a longer containment period. Sensitivity analysis can also provide further insight into the behaviour of the GDF system. In OPERA, the impact of varying parameter values for the waste form and the Boom Clay is used to provide these insights and the sensitivity of predicted doses to changes in a range of different parameter values has been studied [Rosca-Bocancea, 2017; Schröder, 2017: NRG732/746]. The main variations were summarized in in Table 8-4-1. The discussion below focuses on the containment period of the supercontainer, the release rates and diffusion rates in the host rock.

8.5.1 Container failure and release

Both the early (1,000 years) and late (70,000 years) supercontainer failure subcases are very comparable to the base case; the greatest difference is that the maximum values occur somewhat later (respectively at 190,000 and 260,000 instead of 220,000 years). The maximum dose in the early case is about 6% higher than the base case; the late case is about 6% lower. This can be explained by the contribution of Nb-94, since its half-life (20,000 years) is relatively short compared to Se-79 and I-129.

Figure 8.10 compares the results of three parameter variant cases. The only waste form that is assumed to limit release rates is vitrified HLW, which is assumed to dissolve gradually over a period of about 20,000 years (DU-case). Figure 8.10 shows a calculation case (EBS-1) with the fast (almost instant) release from vitrified HLW and an early container failure. The release rate is 3.8×10^-3 per year, i.e., the vitrified waste is assumed to dissolve within 260 years after a containment period in the supercontainer of 1,000 years. This case results in a negligibly higher peak exposure in the biosphere (red line) compared to the default value (DV) case – the black line in Figure 8-10. Consequently, radiological impacts in the biosphere from the disposal system are not sensitive to an instant release of radionuclides from vitrified waste.

The impact of a much slower dissolution rate of 1.6×10^-7 per year is determined by another radionuclide in HLW, I-129, which is expected to dominate the release rates and diffusion rates in the host rock. The chemical evolution of these materials is expected to be very slow, since the diffusive nature of transport processes is limited by the durability of the cementitious materials, low diffusion value of concrete and the potential of the EBS for retardation.

8.5.2 Host rock diffusion rates

For the host rock, the calculated results described so far have used median values for diffusion rates in the Boom Clay. Figure 8-11, shows a calculation case using maximum values for diffusion rates and minimum values for sorption for all radionuclides. The different cases of the normal evolution scenario all assume that there is no containment period for LILW. Even with these early releases, using maximum diffusion values results in no significant contribution to the dose rates in Figure 8-7 from any of the radionuclides in LILW. A number of differences to the results shown are evident.

First, there are separate, small peaks from Re-186m and K-40, since the assumed diffusion rates for these radionuclides are now almost two orders of magnitude larger than those of iodine and selenium. The main peak is a little earlier (at about 150,000 years) and a factor of about two higher than in the base case and is dominated by Se-79 and I-129. In addition, Cs-135 becomes the main contributor between 700,000 and 2.5 million years.

Note that compared to the median values, the maximum diffusion rates for I-129 and Se-79 vary much less than those of the activities. Perhaps the most notable difference, therefore, is the increasing contribution from actinides after 1 million years, mainly from depleted uranium. This is not visible in the base case in the assessment period of 10 million years. Uranium daughters reach the biosphere after 1 million years. The calculated individual dose contributions of uranium and its daughter radionuclides from the GDF are about 1×10^-4 Sv per year after 10 million years is, however, still negligible compared to the present-day natural exposure to uranium series radionuclides in the Dutch population of 1×10^-7 Sv per year, as described in section 3.1. Box 8-1 presents an estimate of the peak dose resulting from uranium and its daughter radionuclides.

8.6 Simplifications in the safety assessment

The following section highlights assumptions made in order to simplify the safety assessment at the present stage. Most of these simplifications consist of not taking credit for potentially positive processes that could enhance predicted safety levels but are not yet sufficiently understood or quantified to allow their use in a robust assessment. Some simplifications, however, relate to effects that could potentially be negative. Further study of such effects must be included in R&D work following on OPERA.

8.6.1 Waste-Engineered Barrier system

Cementitious materials are the dominant component of the engineered barrier system; these are porous systems with physical and chemical properties which will not allow the free transport of radionuclides. It is expected that by further including transport mechanisms for radionuclides within the EBS, a more gradual release of insoluble radionuclides would take place, because of the durability of the cementitious materials, low diffusion value of concrete and the potential of the EBS for retardation.

- Durability of the cementitious materials
  - The chemical evolution of these materials is expected to be very slow, since the diffusive nature of transport processes in the surrounding Boom Clay will limit the rate...
and which corrosants can be transported into the EBS or corrosion products transported out. Congruent dissolution of concrete may be a better conceptual model for determining the release rate of radionuclides contained in cement-based materials. The OPERA assessment has conservatively ignored the fact that a gradual release of radionuclides from cement materials is to be expected – instead, most of the radioactivity is assumed to be immediately available to diffuse through the EBS into the Boom Clay.

- Low diffusion value

Intact CEM-1 concrete, as used in the supercontainer, has a pore diffusion value of $4 \times 10^{-11} \text{ m}^2/\text{s}$ [Kursten, 2015], which is about 5 times lower than the pore diffusion value in undisturbed Boom Clay. The supercontainer concrete were to be made with fly ash or blast furnace slag (BFCS) it would have an even smaller permeability and diffusion value than CEM-1 [Gascoyne, 2002; Verhoef, 2016c]. Fly ash based concrete is proposed for the concrete liner and blast furnace slag based concrete is used by COVRA for conditioning the waste.

- Retardation mechanisms

In the safety assessment, Se-79 dominates the dose contribution because, in the model, selenium is not retarded in the Boom Clay. However, in the European research project FURMIG [Breynaert, 2010] evidence was found of retardation of selenium under reducing conditions in clay formations. In the OPERA R&D programme, further study of the retardation mechanisms of selenium has been carried out, which appears to depend on a combination of minerals [Hoving, to be published]. Retardation of selenium could significantly reduce the calculated doses and, therefore, the assumption that selenium is not retarded in Boom Clay under representative geological disposal conditions remains an important topic for further study.

- Constant climate

In OPERA, stylised biospheres for different climates have been studied [SCOS13 & NRG7232]. Also, the effect of different climates on travel times has been estimated [Valstar 2017]. Both studies look at different climates, but assume a constant climate throughout the safety assessment period. The impacts of major changes in climate, such as glaciations, have not been included in the safety assessment calculations so far. A prolonged interglacial due to global warming, the next extensive ice-sheet in the northern hemisphere is not expected to develop until after 100,000 years. The effect of ice loading of the Boom Clay is envisaged to increase advective flow. There is always a very small advective movement of pore waters in the Boom Clay but, without ice loading, the movement of radionuclides will be dominated by diffusion. In the previous research programme CORA, the mechanical properties of the Boom Clay have been used to model the impact of ice loading on advective flow [Wildenborg, 2000 & 2003]. OPERA has not taken this into account, and this may affect calculated outcomes after about 100,000 years.

- Boom Clay

8.6.2.1 Gas generation and dissipation

In the assessment model, transport of radionuclides in Boom Clay takes place purely by diffusion. If a build-up of gas were to occur in the GDF, it might result in gas-enhanced transport of radionuclides through the Boom Clay, particularly if the gas pressure built up and caused preferential pathways to form through the clay. This has not yet been studied in OPERA in sufficient detail to include it in the safety assessment. If the gas transport might result in a disturbance in which the clay fabric is damaged, then the possibility of self-sealing of clay also needs to be taken into account. The potential impact of hydrogen gas formation can also be limited by repository design and by adaptation of waste processing, but such measures could increase the costs of waste disposal.

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Other experiments also imply that reduction of uranyl carbonate might occur in Boom Clay, which would strongly decrease the mobility of uranium.

The complex redox behaviour of uranium and its carbonate species results in uncertainties in the solubility and sorption behaviour that can only partially be resolved without further experimental research. One consideration to improve the current understanding of uranium mobility is to take specific account of the sorption of uranyl carbonate - based on recent experimental research - in the model used to derive the Kd values for the OPERA safety assessment. More detailed study of the speciation and behaviour of naturally occurring uranium in the Boom Clay would also provide direct evidence as to its fate.

The overall conclusion of these calculations is that uranium will be contained in the Boom Clay for as long as the formation is there. Furthermore, any migration of uranium and its daughters, even after hundreds of million years, is not likely to change background radiation levels significantly. This is what is observed in the Cigar Lake uranium ore deposit in Saskatchewan, Canada. The deposit is contained in a small clay-rich halo at 450 metre depth surrounded by a water-saturated sandstone. No uranium from the one billion year old deposit has been found in the biosphere [Come, 1989].
The OPERA programme has been carried out to progress and support national policy, which calls for eventual geological disposal of Dutch long-lived radioactive wastes. It builds on earlier work on geological disposal (the OPLA and CODRA programmes) and is intended to be the first stage in a long-lasting, iterative programme of RD&D that can lead to construction of a GDF in the Netherlands.

This chapter provides a synthesis of the scientific and technical aspects of disposal, draws conclusions on them and looks forward to future developments. The synthesis and conclusions on societal issues can be found in a separate, complementary synthesis report [Heuvel van den, 2017]. This report by the OPERA Advisory Group also provides recommendations on how societal issues should be dealt with in future projects.

The OPERA Safety Case has gathered and integrated a considerable amount of existing information and carried out a wide range of new studies into one possible GDF concept that is designated to contain the expected inventory of radioactive wastes that will arise over the next decades, constructed in one potential host rock – the Boom Clay.

9.1 Aims of OPERA
The overall aims of the OPERA project and the safety case in particular have been to:
- show that appropriate engineering designs for a GDF can be developed that would be feasible for construction at depths of about 500 m depth in the Boom Clay formation in the Netherlands;
- implement a state-of-the-art methodology for producing a GDF safety case using the capabilities of national expert organisations in the Netherlands and abroad;
- use these current best practice safety case methodologies to show that acceptable levels of long-term safety are achievable for disposal of all the wastes in the Dutch inventory;
- use the results of these engineering and safety evaluations to identify further R&D needs that will progressively enhance design and underpin future iterations of the safety case;
- communicate the approach to implementing geological disposal and to assessing its safety in a comprehensive set of documentation, including this high-level overview, which is intended to be transparent to all parties.

To proceed with the phased development of a geological disposal programme in the Netherlands, OPERA has gathered and integrated a considerable amount of existing information and carried out a wide range of new studies out into one possible GDF concept that is designated to contain the expected inventory of radioactive wastes that will arise over the next decades, constructed in one potential host rock – the Boom Clay.

The project has developed a conditional safety case - conditional because it is not site specific (no GDF location will be selected for many decades), it is based on a simple outline design for a feasible GDF concept and the evaluation contains some significant areas of uncertainty. The experience gained in conducting OPERA is intended to guide future work that will progressively address these conditional factors and allow future safety cases to become more refined.

9.2 Feasibility of constructing a GDF in the Boom Clay
The OPERA GDF concept is based on the well-developed Belgian (ONDRAF/NIRAS) GDF design for Boom Clay, but its construction is proposed to be at twice the depth of the Belgian underground research facility in the Boom Clay. A depth of about 500 m is typical of many national geological disposal programmes in Europe. Increasing depth adds to 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 500 m depth, but more needs to be known about the nature and variability of Boom Clay properties and 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 (TBM) can be used to excavate the GDF. However, the current design present in this OPERA Safety Case includes layout and tunnel features that are impractical for a TBM and 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 this 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 liner, as well as other components of the engineered barrier system, including relatively novel applications (e.g. foamed concrete). These options will allow tailoring and optimisation of the GDF design in the future.

Existing international studies already show that there are practical techniques for sealing tunnels and shafts in a GDF and it is expected that considerably more progress and operational experience will be available over the next 100 years before these techniques need to be deployed in the Netherlands.

One area that requires further consideration is the most appropriate way to move and dispose of large, heavy waste packages underground. Methods are available, but this topic will need much further evaluation and development. Again, the long timescale to GDF implementation means that this is not an urgent issue.

Overall, there is considerable scope to adapt and optimise the engineering design of the GDF. One R&D need is expected to be that the eventual design (should Boom Clay be chosen as the host rock) will be significantly further developed from the OPERA concept.

9.3 The objective and design of the OPERA GDF
The OPERA concept is for a GDF that will contain all high-activity and long-lived radioactive wastes that are currently in storage in the Netherlands and likely to be generated over the next 100 years.

The safety concept for this GDF aims to ISOLATE and CONTAIN the radioactivity in these wastes so that their radioactivity and toxicity will never cause an unacceptable risk to people or the environment. The hazard potential of the wastes [their capacity to cause harm if people come into contact with them] is initially extremely high, but diminishes rapidly over the first hundreds of years after they are placed in the GDF, then more slowly over future thousands of years. The concept thus places emphasis on assuring complete isolation of the wastes over the early period, and recognises that small amounts of radioactivity will eventually move into the surrounding geological and surface environment in the far distant future as the GDF degrades through natural processes. The multiple safety barriers in the concept ensure that any release will be so small that they can cause no harm to future generations.

The GDF system comprises the ‘engineered barriers’ of the GDF itself, situated in the ‘natural barrier’ provided by the Boom Clay and the surrounding geological formations. The engineered barriers comprise a small amount of waste surrounded by almost 100
9.5 How the OPERA GDF to is expected to perform

As noted above, the most critical time over which the performance of the GDF system has to be assured is the first few hundreds to a few thousand years, owing to the initially high hazard potential of the wastes.

However, assessments are able to look much further into the future and consider how the GDF will continue to perform for tens and hundreds of thousands of years. Eventually, anticipated changes in the natural environment, particularly those associated with future glacial cycles, make quantitative estimates of future performance less useful, as their timing and durations are uncertain.

Nevertheless, in common with other international safety cases for geological disposal, we present environmental impacts for the next million years. At such long times, it is appropriate to use other indicators of performance rather than calculated radiation doses to background radiation exposures. Two radionuclides contribute significantly to exposures - but in the NES these factors are very long and the half-lives of the two main contributors to radiation exposure mentioned above are very long (Se-79 is 327,000 years; I-129 is more than 16 million years).

A key observation is that, within a few hundred thousand to a million years, almost all of the radioactivity initially in the GDF has decayed either within the GDF itself or in the Boom Clay, only a tiny fraction of it is still available to be released to the overlying geological formations and biosphere. The GDF has effectively performed its isolation and containment task by this time.

The expectation is depleted uranium (DU). Its principal radionuclide (naturally occurring U-238) has a half-life that is so long that it performed its isolation and containment task by this time. The exception is depleted uranium (DU). Its principal radionuclide (naturally occurring U-238) has a half-life that is so long that it performed its isolation and containment task by this time. The reason for this is clear. The half-lives of the two main contributors to radiation exposure mentioned above are very long (Se-79 is 327,000 years; I-129 is more than 16 million years). Consequently, these radionuclides do not decay significantly even with longer containment in the supercontainer. In practice, these radionuclides never present a significant hazard since their concentrations are reduced to very low levels by dispersion and diffusion in the clay, and dilution in the overburden. Nevertheless, some scope for optimising the EBS exists, particularly if one considers scenarios other than the OPERA reference evolution scenario. Longer container lifetimes mean that the times of failures of all the containers would be spread across thousands of years, reducing the release rates from the GDF and subsequently the peak exposures, which are currently influenced by the pessimistic assumptions about simultaneous failures, combined with instantaneous availability of all radionuclides. The combination of potentially longer lifetimes, lower dissolution rates of the vitrified HLW and Se-79. However, it seems unlikely that further refinement of the performance assessment calculation only by using less pessimistic assumptions about the performance of the GDF in the future would reduce impacts below the calculation calculated for I-129. The I-129 peak is influenced principally by assumptions about the properties of the Boom Clay. Nevertheless, for future work, it is proposed to include assessment of 2 glacial cycles of different severities after 100,000 years and within the next million years. The impacts for deep erosion by sub-glacial meltwater channels at the end of an ice age have been raised as a significant issue for a GDF, even at 500 m depth. This scenario is one aspect of the climate impact assessment described in the previous point. An evaluation needs to be made to see whether an event could occur, the hazard potential of the wastes at that time, the location of radioactivity in the GDF system at that time, potential erosion and mobilisation mechanisms, the possible dose consequences and the likelihood of occurrence of such an event. The outcome of the analysis would be reported in terms of health risk (rather than exposures), to enable a risk-based approach to be made on the significance of the scenario to the GDF concept and to eventual site considerations.

4.7 Conservatisms and open issues in the OPERA safety case

As noted in the previous discussion, the reference case NES on which the present safety case calculations are based contains several conservatisms that lead to over-estimation of the impacts of failures and peak potential exposure values that the range of cases that can be considered. In key conservatisms are:

- All containers of any specific type fail at the same time, and
- No radionuclide sorption outside the Boom Clay in the overlying geological formations;
- Relatively rapid dissolution of the vitrified HLW (CSD-v), implying high availability of all radionuclides to enter solution once a container fails;
- Simultaneous failure of all waste containers within a waste family;
- Easy solution of Boom Clay pore waters with the cement and concrete of the GDF, leading to early degradation of its containment properties.

At the same time, it is acknowledged that a number of processes and events that might lead to greater predicted impacts have not yet been treated in this stage of OPERA and thus constitute open issues that will require further R&D and safety assessments. These include:

- A full assessment needs to be performed of "altered evolution scenarios" that might lead to behaviour different from that calculated and assumed in the reference case. Climate evolution and future glacial cycles are expected, but not yet included as part of the NES, which assumes continuation of the current climate. Permafrost and periglacial cover need to be further evaluated. However, there is good reason to believe that the current interglacial will last for more than 100,000 years - well beyond the period of high hazard potential of the wastes. Nevertheless, for future work, it is proposed to include assessment of 2 glacial cycles of different severities after 100,000 years and within the next million years. The impacts for deep erosion by sub-glacial meltwater channels at the end of an ice age have been raised as a significant issue for a GDF, even at 500 m depth. This scenario is one aspect of the climate impact assessment described in the previous point. An evaluation needs to be made to see whether an event could occur, the hazard potential of the wastes at that time, the location of radioactivity in the GDF system at that time, potential erosion and mobilisation mechanisms, the possible dose consequences and the likelihood of occurrence of such an event. The outcome of the analysis would be reported in terms of health risk (rather than exposures), to enable a risk-based approach to be made on the significance of the scenario to the GDF concept and to eventual site considerations.

- The NES has looked at radionuclide movement in periglacial channels at the end of an ice age have been raised as a significant issue for a GDF, even at 500 m depth. This scenario is one aspect of the climate impact assessment described in the previous point. An evaluation needs to be made to see whether an event could occur, the hazard potential of the wastes at that time, the location of radioactivity in the GDF system at that time, potential erosion and mobilisation mechanisms, the possible dose consequences and the likelihood of occurrence of such an event. The outcome of the analysis would be reported in terms of health risk (rather than exposures), to enable a risk-based approach to be made on the significance of the scenario to the GDF concept and to eventual site considerations.

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9.9 Improving the design and the safety case

There are uncertainties in several areas of OPERA, and assumptions and simplifications have been needed to establish the safety assessment models and calculations, but these have mostly been taken into account by assuming poorer performance than we actually expect, as discussed above.

The principal uncertainties have been identified as work progressed in each of the OPERA work packages and they will be addressed by future OPERA studies. The main areas identified for further work to be:

- Improving knowledge of the lithological, geotechnical, hydrogeological and geochemical properties of the Boom Clay at disposal depth by testing and sampling in boroholes;
- Taking reliable porewater samples in the Boom Clay and under- and overlying formations to gather palaeohydro-geological data (e.g., environmental isotope) to understand and quantify rates of diffusion and deep flow and transport in and around the Boom Clay;
- Measuring in situ stresses and hydraulic pressure gradients in the Boom Clay at disposal depth and their evolution;
- Compiling further information on the presence and behaviour of natural gases in formations below the Boom Clay and in the Boom Clay itself;
- Evaluation of the generation and behaviour of corrosion gases in the engineered barrier system and their behaviour in the Boom Clay;
- Improving understanding of the nature and rates of interactions between the Boom Clay and the GDF tunnel liners and other cement-based barriers;
- Testing alternative formulations of cement and concrete for EBS components that would be appropriate for the environmental conditions in the deep Boom Clay;
- Definition and evaluation of alternative GDF design concepts that might be suitable for the Boom Clay;
- Performing analyses of additional ‘altered evolution’ scenarios, especially those for different climate states;
- Developing viable systems for moving and emplacing waste; we live in an imperfect world and human-kind has evolved in a naturally radioactive environment.

At a broader scale, natural radioactivity, present in all rocks, soils and waters around us, provides a useful yardstick against which to compare the impacts of wastes in the GDF. Natural radioactivity levels in the Netherlands are typical of those across Europe and the unavoidable natural radiation exposures to which we are all subject are higher than those from even our pessimistically calculated releases. We live in an imperfect world and human-kind has evolved in a naturally radioactive environment.

In the very far future (many millions or hundreds of millions of years), we expect the degraded GDF with its considerably reduced radioxenic hazard to have similar properties to a uranium ore body, containing mainly the residues of the depleted uranium wastes. It will either become more deeply buried and isolated in Earth’s crust by further deposition of sediments, or it will be eroded away by natural processes, with its contents being distributed among and becoming part of the natural radioactive background.

Confidence in the reliability of our performance assessment calculations is also enhanced by the fact that they are broadly similar to those estimated independently for a wide range of waste disposal sites and how risk is assessed. For example, they are closely comparable with the impacts calculated for the proposed Belgian GDF, also in Boom Clay. These similarities show the generically high level of containment and isolation provided by geological disposal.

9.10 Overall conclusions

Over the seven 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.

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 and they support a decision to work further on this concept. The approach to steer GDF development with a series of iterative cases is sufficiently flexible to handle any likely future inventory changes, or to respond to changes in disposal schedule.

The OPERA GDF concept, if eventually implemented at a well-chosen site with an appropriate geological setting, is capable of providing high levels of safety that match those estimated in other national programmes and would easily meet national and international standards for this type of facility for a normal evolution scenario.

Predicted radiation exposures of people are 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 radioxenic elements will not be affected today or in the future.

In this sense, a GDF implemented in the Boom Clay at around 500m depth can clearly fulfil its task of permanently isolating Netherlands wastes and protecting current and future generations in case of a normal evolution scenario.

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 begun its work on CODRA, which will be the basis for future work. This is perhaps the greatest area of technical uncertainty in the OPERA work to date.

OPERA has focussed upon the Boom Clay: salt formations and other clay formations are also viable options for a GDF. Salt has been explored in the past in the Netherlands 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 (e.g., work on waste types, inventories, packaging, overlying geological formations, safety assessment modelling etc.).

9.11 Looking forwards

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

Major programmes such as OPERA have been completed in the past (OLPA, CODRA), but there has been no continuity to maintain expertise. This situation needs to be avoided in future. 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. In this respect, a Road Map has been prepared and is presented in Chapter 10.

Finally, we note that the present report is a scientific/technical document, describing the 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. Globally, the greatest obstacles to geological disposal have been those related to achieving sufficient public and political support. OPERA has initiated work on communication with the Dutch public, to which this report is a contribution, and this important activity will be continued in future projects.

Although this requires further assessment, it is observed that the international studies examined suggest it is not likely to be a major issue in the safety cases.

However, the Dutch inventory means that the specific case of fast gas generation from corrosion of aluminium in Spent Research Reactor Fuel needs to be evaluated further.

The potential for criticality to occur in regions of the GDF holding enriched SRIF and the consequent risks have not yet been assessed. Such scenarios would require the mobilisation of fissile materials from the SRIF and their unlikely local re-concentration within some region of the EBS in configurations that could allow criticality to occur.

OPERA has looked at the impacts only of radioactive elements that might be present in the biosphere from the GDF. There are also chemically toxic components in the waste materials that could have health effects if they migrate to the biosphere and this requires evaluation.
How to manage the necessary knowledge to support the long-term decision making about disposal?

10.1 Organisation of RWM in the Netherlands: roles of the parties

With a policy of long-term interim storage, for period of at least 100 years, it is necessary to plan and transparently lay out the decisions leading towards implementation of geological disposal of the Dutch radioactive waste. This is being done by developing a roadmap and assigning the different responsibilities to the actors involved. In Europe, the institutional arrangements for the management of radioactive waste typically follow the classical IAEA triangle. The model separates the three roles of the regulator, waste generator, and waste organisation. Each has separate responsibilities and must exhibit independence from the other.

**Regulator**

The nuclear sector in the Netherlands is regulated by the Authority for Nuclear Safety and Radiation Protection (ANVS), established in 2015. The ANVS, an independent administrative authority, prepares policy and legislation for radioactive waste, develops safety requirements, issues licenses and carries out inspections. Complying with the Directive 2011/70/EURATOM [EU, 2013], the ANVS has prepared the National Programme on radioactive waste management.

**Waste generator**

In general, waste prevention and reuse of materials is an important environmental goal. Waste generators are required to prevent the generation of radioactive waste as much as reasonably achievable. Radioactive materials for which no use, reuse or recycling is foreseen, are to be transferred to COVRA. The waste generator has to pay the waste fees and notify the COVRA of the type and amount of wastes being produced. The generator prepares the waste according the waste acceptance criteria set by COVRA.

**Waste organisation**

The government founded COVRA in 1982 to manage radioactive waste in the Netherlands from collection to final disposal. COVRA owns the radioactive waste and, as a result, is responsible for development and implementation of the disposal facility. COVRA takes all the necessary steps to prepare for the longer term, including conducting research on disposal and ensuring sufficient financing. In principle, all the costs for radioactive waste management are borne by the waste generators, including the expected costs of waste disposal and of supporting research into geological disposal. These costs are charged to the waste generators through COVRA’s fees. Periodically, COVRA will update its cost estimates of the GDF to take account of the international–state-of-the art and to ensure the fees cover these costs. For the periodical revision and peer review of the National Programme, outcomes of research on geological disposal are essential. About two years in advance of each evaluation, COVRA intends to report on the current state of knowledge on disposal in the Netherlands; this will be done in the framework of a formal Safety Case (SC).

**Other actors**

The national, regional and municipal governments have together taken a responsibility for defining the decision-making process towards geological disposal and have to agree on the roles and responsibilities of the specific levels of government and officials. Researchers and the public do not have a direct responsibility in the implementation or decision-making process, but they have important roles that are highly dependent on the stage of development of the geological disposal programme.

The roadmap focuses on the development of scientific and technical knowledge. The development of the wider, societal issues of disposal, including stakeholder engagement and conditions for an inclusive process for long-term decision-making on disposal is dealt with in a separate synthesis report by the OPERA Advisory Group [Heuvel van den, 2017].

**10.2 Drivers for the COVRA GDF programme**

The roadmap is aligned with the decision-making process on geological disposal of radioactive wastes (Figure 10-2). Choices and decisions are made in the development of a disposal concept over a very long period. The argumentation for these choices and decisions must be traceable to validated documentation and research, even after many years in which scientific and societal insights may have changed. Also, the right of autonomy and self-determination implies that crucial information must not be withheld from future generations and that knowledge about the waste generated and the future GDF must be kept alive and accessible. Therefore, to support the decision-making process, robust and consistent knowledge management is necessary. An essential part of the knowledge management is an active, continuous research programme on geological disposal. Figure 9-2 shows that the definitive decision on the disposal method will be taken around 2100.

The period of aboveground storage will provide time to learn from experiences in other countries, to carry out research and to accumulate the knowledge to make a well-founded decision. A choice for location or host formation can only be made after the decision for the disposal method and the research up to then will remain at a conceptual level. COVRA will make conditional generic (i.e. non-site-specific) safety cases during the next decades. In this period, the principal driving forces for research are to:

1. Strengthen the confidence in the safety of disposal: investigating the different host rock options (e.g. rock salt, Bloom Clay and Ypresian Clay), potential GDF design options, the post-closure performance, and level of the public confidence and acceptability.
2. Assess the disposability (see Box 10-1) of different waste and waste packaging families: investigating waste packaging options and requirements on collection, treatment and conditioning of waste families to facilitate their eventual disposal.
3. Ensure adequate funding for disposal, based on regularly updated cost estimates for the GDF: identifying and where possible optimizing cost-determining features of a GDF.

**Steering research using the safety case**

COVRA is responsible for development of the safety case and will use the safety case as an instrument to steer research and manage the knowledge over decades. Conditional safety cases will be developed and periodically updated for a GDF in rock salt and in poorly indurated clay, such as the Boom Clay and the Ypresian Clay. As part of the safety cases, COVRA will carry out performance assessments to assess the relevance of knowledge and research for the post-closure safety of the GDF in the different possible host rocks.

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Figure 10.1: Institutional arrangements according to the classical triangle
Establishment COVRA

Knowledge infrastructure and community

About twenty research entities and many different researchers in the Netherlands and abroad have contributed to OPERA. Meetings were organized to share their experience and knowledge. In the future, COVRA will continue to rely on national research entities as well as other national disposal programmes to provide the basic conceptual understanding of processes taking place in the post-closure phase, carry out experimental investigations and provide input data for theses assessments. COVRA will also participate in international groups such as the Nuclear Energy Agency Clay and Salt Club, in European projects such as European Joint Programming and collaborate with its sister organisations abroad. COVRA will also encourage organisations involved in the future research to share their work and experience in international fora and scientific journals. In this way, the necessary knowledge management infrastructure and community can be maintained over the long term.

10.3 Key topics

The required level of safety for a GDF will be determined by national and international regulations and guidelines. However, the question what level of safety is acceptable is determined by societal processes and must be provided by the containment of the different barriers in the disposal system. In the previous chapters, current knowledge on the performance and evolution of compartments (chapters 6 and 7) and their contribution to safety was assessed (chapter 8). Based on that assessment the key topics for future research were extracted. Figure 9-3 shows the key topics for each component in the disposal system; these are described below in more detail.

Society

Integrating societal aspects into technical research. Acceptability of geological disposal and confidence in the (long-term) performance of a GDF will remain key topics for the next decades.

While it is important to involve stakeholders in the public from the start of a disposal programme, it is difficult to motivate their active involvement before concrete proposals directly affecting them are on the table - e.g. a final disposal concept and site. Nevertheless, experience over the past decades has shown that in the search for disposal solutions, technical-scientific research is a necessary but not sufficient condition to implement a GDF. A widely supported solution is necessary, taking into account also what is societally acceptable and morally responsible. Emotions and moral values play an important role because they can provide boundary conditions and important objectives for the technical developments. The technical-scientific research should, therefore, be coupled to ethical and societal research. One concrete example of a socio-technical challenge is the introduction of the notion of reversibility and retrievability or (long-term) repository monitoring. When such an event could occur, the hazard potential of the wastes contained, and no diffusion takes place. Research to quantify the containment of radionuclides in the Netherlands at the current outline concept. This also applies to other host rocks.

Surrounding rock formations

Salinity in deeper groundwater model. The National Hydrological Institute was extended in OPERA in order to calculate the potential transport of radionuclides between the Boom Clay and the biosphere. The surrounding rock formations for a GDF at suitable disposal depth are expected to be Falunsøren aquifer systems. The knowledge available on these aquifers indicates that these systems are saline. Incorporation of the salinity in the extended model would result in a more realistic (and less conservative) estimate of radionuclide releases.

Effect of climatic change. In OPERA, potential hydrogeological behaviour as a function of a changing climate and glacial cycling has not been assessed. The retreating ice may locally deeply erode the surrounding rock formations and provide large amounts of meltwater available for dilution. An evaluation needs to estimate when such an event could occur, the hazard potential of the wastes at that time, the location of radioactivity in the GDF system at that time, potential erosion and mobilisation mechanisms, the possible dose consequences and the likelihood of occurrence of such an event. The outcome of the analysis would enable a risk-informed judgment to be made on the significance of the scenario to the GDF concept and to eventual site selection considerations.

Host rock

The host rock forms the main barrier in disposal concepts for both clay and rock salt. Improving knowledge on how it preforms and evolves is critical to understand and quantify its ability to contain radionuclides over long times. Priority should be given to confirming the main assumptions underpinning the safety concepts and feasibility of a GDF in both poorly indurated clays (Boom and Ypresian Clay) and Zechstein Rock salt. This necessitates research aimed at a better understanding of:

- Geotechnical properties. Geotechnical assessment within OPERA indicates that a stable and robust GDF can be engineered and operated at 500 m depth, but that more needs to be known about the nature and variability of Boom Clay properties and the in-situ stress regime on a regional basis across the Netherlands to refine the current outline concept. This also applies to other host rocks. Geotechnical properties of interest include thermal and mechanical properties.
- Diffusion-dominated transport. Because of the low permeability of clays, water movements are slow, and transport of radionuclides is slow, and transport of radionuclides is expected to take place predominantly by diffusion. Research should focus on quantifying diffusion through clays in the Netherlands at disposal depth and evaluating the potentially disruptive processes, such as the transport of corrosion gases in the in the Boom Clay. Rock salt exhibits a very low permeability and is impervious (i.e. no or very limited interconnected pore space) to liquids and gasses. Under normal evolution conditions, waste is permanently contained, and no diffusion takes place. Research to quantify the containment and evaluate the behaviour of corrosion gases is also of interest for rock salt. Recommendations for further research on rock salt has been made in OPERA (Hart, 2015b).
- Retardation. In clay retardation of radionuclides is expected to take place by sorption on clay minerals and by precipitation of solubility limited elements. Retardation is, among others, dependent on the elemental speciation of radionuclides. Of most interest here are the elements Sr and U. Research should focus on the speciation of these elements under conditions as present in clay pore water at the intended disposal depth. Furthermore, on characterisation of
natural radionuclides and chemical analogues of artificial radionuclides measured in the poorly indurated clays in the Netherlands may require further understanding and specific quantitative knowledge of potential processes taking place in the deep underground. Research should focus on improving understanding of the nature and rates of interactions between the Boom Clay and the GDF and the transferability of the design to Ypresian Clay and, in particular, to poorly indurated clay.

To provide sufficient experimental evidence of critical processes and the applied parameter values in the assessment model for the normal evolution of the GDF in poorly indurated clay in the Netherlands may require several decades of further work, because it requires further understanding and specific quantitative knowledge of potential processes taking place in the deep underground. Research should focus on improving understanding of the nature and rates of interactions between the Boom Clay and the GDF and the transferability of the design to Ypresian Clay and, in particular, to poorly indurated clay.

Waste package design. Waste packaging for disposal adds significantly to the volume to be disposed of, in case of the supercontainer. The current OPERA design includes layout and tunnel features that significantly contribute to the volume to be disposed of, in case of the supercontainer. Waste packaging for disposal adds significantly to the volume to be disposed of, in case of the supercontainer. To provide sufficient experimental evidence of critical processes and the applied parameter values in the assessment model for the normal evolution of the GDF in poorly indurated clay in the Netherlands may require several decades of further work, because it requires further understanding and specific quantitative knowledge of potential processes taking place in the deep underground. Research should focus on improving understanding of the nature and rates of interactions between the Boom Clay and the GDF and the transferability of the design to Ypresian Clay and, in particular, to poorly indurated clay.

Repository layout. Existing tunneling techniques using a tunnel-boring machine (TBM) can be used to excavate the GDF. However, the current OPERA design includes layout and tunnel features that are impractical for a TBM and the working design will need to be refined and optimised progressively, as more information on the Boom Clay becomes available.

10.4 shorter-term objectives

From the list in section 9.3 of key topics to be further investigated, it is important for planning and budgeting reasons, to identify specific objectives for the next decade. These are to (further) develop the performance assessment capacity and to work on the key topics that have been allocated highest priority, i.e. host rock, society and engineered barrier system. COVRA will start in host rock formations for which most information is available, Boom Clay and Zechstein rock salt, and will work on Ypresian Clay later.

Safety case and post-closure performance

Boom Clay safety case

An update of Boom Clay safety case is planned for 2023. The current OPERA safety case for Boom Clay is limited to the Normal Evolution Scenario and does not assess the altered evolution scenarios. Analytical processes that might change the calculated fate of radionuclides, e.g. gas generation, criticality and ice ages are needed to complement the normal evolution scenario. Events that lead to altered evolution scenarios need to be studied and calculated as well for the example intrusion into the GDF by people in the distant future and deep erosion during the retreat of ice caps. A continuous, rather than instantaneous, release model for radionuclides leaving the Engineered Barrier System (EBS) would make the calculations less conservative. Development of these more comprehensive assessment would build on knowledge gained in OPERA and will assist in further refinement of research priorities.

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Waste package design. Waste packaging for disposal adds significantly to the volume to be disposed of, in case of the supercontainer for the different types of HUL. An optimization of the container taking account of characteristics of different types of HUL or the use of depleted uranium as an aggregate in the container (basalt) may significantly reduce the repository footprint. Supercanisters have been designed for Boom Clay, the transferability of the design to Ypresian Clay and, in particular, to rock salt has to be investigated.

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Repository layout. Existing tunneling techniques using a tunnel-boring machine (TBM) can be used to excavate the GDF. However, the current OPERA design includes layout and tunnel features that are impractical for a TBM and the working design will need to be refined and optimised progressively, as more information on the Boom Clay becomes available.
a way to make use of the available knowledge and expertise of different stakeholders. Research is foreseen around the following socio-technical challenges.

Retrievability. The notion of retrievability was originally introduced into Dutch policy in 1993 in order to meet requirements expressed by stakeholders at that time for emplacement of waste packages and closure of the GDF. The concept has evolved since then to also address issues such as intergenerational equity, autonomy and self-determination. Research should focus on how societal aspects such as ethics and emotions can help to design for retrievability and develop monitoring strategies. Key questions are what adjustments to design and operational procedures should we include now, and what amendments should be left until it is possible to enter discussions with potential host communities in the far future.

Monitoring. For the further development of the monitoring system, the data available from the monitoring activities by drinking water companies can be used. Knowledge within the water companies on monitoring ground water quality, including its natural radionuclide content, can be helpful in developing monitoring systems and criteria intended to assess whether the potential disturbance of the GDF with the chosen engineered barrier system and host rock is negligible. RIVM continuously monitors radiological exposure in the Netherlands and can also provide essential input for developing monitoring criteria and systems.

Concrete evolution. COVRA will investigate collaboration with Dutch archaeological communities to study archaeological evidence of concrete degradation since this may help in the validation of models. In the south of the Netherlands, 2,000-year-old Roman concrete is expected to be present. For geological disposal, knowledge of the exposure conditions of this ancient concrete and access to the soil samples adjacent to Roman concrete could help to better understand the long-term processes around the clay-concrete interface.

Multinational ERDO working group. In the dual track policy of the Netherlands, participation in a shared or multinational disposal facility in Europe is considered. In parallel with the activities for a national GDF, the multinational track of the policy also needs to be progressed. So far, countries without nuclear power or with small nuclear programmes cooperate through the ERDO working group. In this group, knowledge is transferred and joint projects are developed, both of which can lead to more efficient use of RD&D funds. COVRA intends to continue its activities in the working group secretariat.

EURATOM programme. There has been no significant European financial support for projects on multinational disposal, since the SAPIERR projects some 10 years ago. However, the proposed European Joint Programming initiative may present new possibilities and COVRA will support and help coordinate projects with or relevant for other small programmes.

Other key topics. Depending on available resources and priority, COVRA will also support (inter)national initiatives on other key topics (Figure 9-3).

11. References


the European Union L199, 2.8.2011, 48-56.


APPENDIX 1: RESEARCH TASKS IN OPERA

Research tasks have been completed by production of a report. These reports have been published on COVRA’s website in the past seven years. The content of some OPERA reports has also been published in scientific papers.

The aim of WP1 in the OPERA research plan was to define all contextual and logistic boundary conditions for the OPERA Safety case.

WP1: Safety Case context

A physico-chemical description of the waste properties in terms of radioactive inventory and the waste matrix is described in the following reports:


- WP1.1: Waste characteristics
  - Task 1.1.1: Definition of radionuclide inventory and matrix composition

The radioactive inventory from the nuclear research reactors and nuclear power plants Dodewaard and Borsele as accepted by the Dutch parliament was used as input for the safety assessment. The radioactive inventory with alternative future fuel cycles in the Netherlands in compliance with the scenarios formulated in ‘Energierapport 2008’ has been analysed. The result of this analysis is described in the following report:


- Task 1.1.2: Alternative waste scenario’s

The identification of stakeholders and their potential engagement in the radioactive waste management process has been analysed in workshops. The workshops with these stakeholders and recommendations to engage with stakeholders are described in the following reports:


- WP1.2: Political requirement and societal expectations
  - Task 1.2.1: Arena or stakeholder analysis
  - Task 1.2.4: Public & stakeholder involvement

Retrievability of waste is an important prerequisite for the geological disposal in the Netherlands. The following report provides additional input for the general discussion on retrievability, reversibility, staged closure and monitoring that did not fit properly in the main report:


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  - Task 1.2.4: Public & stakeholder involvement

Retrievability of waste is an important prerequisite for the geological disposal in the Netherlands. The following report provides additional input for the general discussion on retrievability, reversibility, staged closure and monitoring that did not fit properly in the main report.

Task 1.2.3: Retrievability and staged closure

Safety assessments are performed as part of the OPERA safety case. The calculated results are compared with safety criteria to judge the safety of the disposal facility. The safety indicators used in the assessment are described in the following report:


Task 1.2.2: Legal requirements

All safety relevant aspects of the disposal concepts, safety assessment results are published in the OPERA safety case. The presence of a well-documented in-depth review that satisfies independent national and international experts does not necessarily mean that the public will be convinced about the safety of a geological disposal concept, too. A communication strategy to present the outcomes of the OPERA to the public is described in the following report:


WP1.3: Communicating the Safety Case

Task 1.3.1: Communicating Safety Case results

The aim of WP2 in the OPERA research plan was to define the overall integrating work packages and to use the developed methodologies to evaluate the current state of the art on a disposal facility in rock salt in the Netherlands.

WP2.1: Safety Case

WP2.1: Definition of the Safety Case

The guidance for the Safety Case is described in the following reports:


WP3: Repository Design

WP3: Repository Design


WP3.1: Feasibility studies

Task 2.1.1: Structure of the Safety Case

A central aspect of the safety case is the execution of a safety assessment. This requires the definition of a sound and consistent methodology, a critical evaluation of assumptions used in the safety assessment calculations, the evaluation of relevant evolution scenarios, the identification and classification of features, events and processes (FEP), the evaluation of uncertainties and the interpretation of calculated results. The overall methodology and strategic framework for the safety assessments are described in the following three reports and excel-sheets:


WP3.2: Design modification (optional)

The disposal concept as proposed at start of the OPERA programme needed to be revised with respect to the construction of tunnel crossings. In addition, the closure and sealing of the disposal facility has been assessed and optimised. The long-term storage period at least 100 years for the waste significantly reduces the heat perturbation in the host rock of heat-generating HLW but still has an impact on the geomechanical behaviour of the host rock i.e. plastic zone and thereby on the distance between the disposal galleries. These three analyses are described in the following reports:


Task 3.2.1: Design modifications

The aim of WP4 in the OPERA research plan was to define the boundary conditions of the near field based on the investigation of all relevant geological and geochemical features of the geosphere at present and their expected future evolution.

WP4: Geology and geochemistry

WP4: Geology and hydrogeological behaviour of the geosphere

A generic description of the present geological and geochemical characteristics and features in the geological environment enclosing Boom Clay and of Boom Clay itself is provided in the following report and scientific paper:


Task 4.1.1: Description of the present geological and hydrogeological properties of the geosphere

The control of Earth’s processes over a time span of 1 million years on geological and geochemical properties of the geosphere that might affect the post-closure safety assessment of a geological disposal facility in Boom Clay in the Netherlands are described in:


Task 4.1.2: Future evolution of the geological and hydrogeological properties of the geosphere

WP4.2: Hydrogeological boundary conditions for the near-field

The evolution of the disposal facility and the waste packages is controlled by the Boom Clay and the surrounding rock formations. The present and future boundary conditions that are superposed by the geosphere to define the model representation for the near field are described in:


Task 4.2.1: Definition of boundary conditions for the near-field model

Task 4.2.2: Favourable hydrogeological settings (optional) - not performed in OPERA

The aim of WPS in the OPERA research plan was to define the boundary conditions of the near field based on the investigation of all relevant geochemical features of Boom Clay at present and the expected future evolution of Boom Clay and to describe the geochemical interactions between Boom Clay and with materials of the disposal facility that are introduced in this host rock.

WP5: Geochemistry and geomechanics

WP1.1: Geological behaviour of EBS

The potential release of radionuclides into the geological formation is assumed to take place as a function of the degradation rate of the waste form in the safety assessment in OPERA. These rates depend on chemical conditions. In a first step, the geochemical conditions of the cementitious near-field were defined. On the basis of the defined conditions, the waste degradation processes and products and their behaviour in the near field were investigated and discussed. A controlled release of radionuclides of HW glasses takes place by dissolution. The aluminium in spent research reactor fuels corrodes at such a high rate at the chemical disposal conditions that an instant radionuclide release with a high hydrogen gas generation rate needs to be assumed. The disposal relevant degradation rates for vitrified high level waste resulting from the reprocessing of spent nuclear fuels from Dutch power plants and for spent research reactor fuels are described in:


G. Dassmann, K. Haneke, A. Filby, R. Wiegers, Corrosion behaviour of spent research reactor fuel under OPERA repository conditions, OPERA-PU-IBR511A (2016) 1-56.

Task 5.1.1: HW waste matrix corrosion processes

• Task 5.1.5: Microbiological effects on the EBS and the Boom Clay

WPS.2: Properties, evolution and interactions of the Boom Clay

The availability of fresh Dutch Boom Clay samples at relevant depth interval was absent in OPERA. In order to say something about the Dutch Boom Clay for disposal, old samples at relevant depth interval from the TNO core house in Zeist were selected to measure the mineralogy and soil chemical composition. Silt crystals have been measured and this result is attributed to the origin of the samples that originally had saline Boom Clay pore water because an increase in the amount of oxides is attributed to the oxidation of pyrite oxidation. The man-made perturbations are the inner oxidation of the initially reduced Boom Clay conditions. Pore water chemistry controls the chemical evolution of engineered barriers and the retention radionuclides. Pore water chemistry and mineralogy affect the sorption and retardation potential of Boom Clay. A saline fresh Boom Clay was available to measure the Boom Clay pore water. The composition of groundwater in formations surrounding the Boom Clay can be used to determine the long-term evolution of Boom Clay. All measurements are described in the following reports and papers:


• Task 5.2.1: Geochemical properties and long-term evolution of the Boom Clay

No large geochemical changes of Boom Clay are expected on a time scale of 1 million years without natural or man-made perturbations. A natural process is formed by postglacial erosion in which the potential oxygenated surface water induces geochemical reactions such as pyrite oxidation. The man-made perturbations are the inner oxidation of the clay during excavation, the alkaline disturbed zone in clay by the introduction of cementitious materials with a high pH in the disposal facility, the conventional waste degradation products and man-made materials such as hydrogen. The measurements in the reports completed for task 5.2.1 have been interpreted to have a set of starting conditions for calculating the geochemical changes in the Boom Clay in the following report:


• Task 5.2.2: Geochanical interactions in the Boom Clay

The thermo-hydro-chemical properties of Boom Clay in Belgium are well defined due to the research conducted in the Belgian underground research facility HADES in Mol and spatially across the country. For Dutch Boom Clay, such research results are scarce. The Dutch pore water chemistry different in salinity from HADES results in different hydro-chemical properties. The disposal depth is expected to be larger in the Netherlands than in Belgium. The effect of greater burial depth in the Netherlands on the mechanical properties has been analysed using Critical State Mechanics. This analysis suggests an increased mechanical stability at larger burial depth. Experiments are performed to provide evidence for this analysis. The analysis and sieving experimental results are described in:


OPERA-BGS523&616 (2017)

• Task 5.2.3: Geomechanical properties and thermo-hydro-chemical evolution of the Boom Clay

The aim of WPS6 in the OPERA research plan was to describe all relevant processes of the migration of radionuclides from the waste through the different compartments to the biosphere.

• WP6.1: Radionuclide migration

WP6.1: Radionuclide migration in the Boom Clay

The speciation of sorbed radionuclides depends on the pore water chemistry. The redox potential is an integral part of the pore water chemistry. And knowledge of the redox properties of Boom Clay is important to assess the capacity of Boom Clay to reduce or oxidize intruding radioactive ions. The redox potential of Boom Clay to retard the progression of redox fronts. Assessing the redox properties of clay-rich sedimentary deposits are described in the following report and paper:


• Task 6.1.1: Fundamental aspects of sorption processes

The model representation for modelling sorption processes that accounts for pH, redox potential, ionic strength, pore water composition, pressure and temperature and the interaction of different surfaces present in Boom Clay and the database with the sorption properties for all relevant radionuclides are described in the following reports:


• Task 6.1.3: Modelling of diffusion processes

An evaluation of the features behind radionuclide diffusion in Boom Clay and a database for the diffusion properties of all relevant radionuclides are described in the following reports:


• Task 6.1.3: Modelling of diffusion processes

Colloids are commonly defined as small particles with dimension roughly between 1 nm and 1 µm. Colloids can represent important sorbents for environmental contaminants keeping them into suspension over long periods of time. In more detail, organic colloids that are known to carry radionuclides in Boom Clay in Mol are considered because of their predominance and special significance. The Dissolved Organic Matter concentration decreases with increasing ionic strength in leaching experiments performed with Boom Clay powder with a minimum in DOM at ionic strength equal to seawater. The transport of colloids, the governing mechanism and processes and the role of colloidal filtration, are extrapolated from the conclusions drawn for Boom Clay conditions at Mol site to the disposal conditions prevailing in the Netherlands in the following report:


• Task 6.1.4: Mobility and presence of colloidal particles
Solute transport by diffusion requires a chemical gradient. Other driving forces for solute transport are a hydraulic gradient and an electrical gradient. The potential impact of these non-diffusion related transport processes and available experimental evidence are described in:


- Task 6.1.5: Non-diffusion related transport processes of solutes in the Boom Clay

Gas can be generated during degradation of waste forms and waste packages such as hydrogen by anaerobic corrosion of metals. The four primary phenomenological models to describe gas migration in clay are gas movement by solution and/or diffusion, gas flow in the original porosity of the clay fabric, gas flow with micro-fissuring by dilation of the clay fabric and gas flow along macro fractures. The four models and scoping experimental results are described in:


OPERA-PU-BG5523&616 (2017)

- Task 6.1.6: Gas migration in the EBS and in the Boom Clay

- WP6.2: Radionuclide migration in the surrounding rock formation

The flow of groundwater is modelled in the Netherlands with the National Hydrological Instrument (NHI). The existing NHI is at a smaller depth than relevant radioactive disposal depth and therefore this groundwater model was extended in the vertical direction to include all relevant geological formations down to and even below Boom Clay. This extension and the modelling approach for radionuclides entering the biosphere are described in the following report and scientific paper:

J.R. Valstar & N. Goorden, Hydrological transport in the rock formations surrounding the host rock, OPERA-PU-DL362 (2017) 1-88, revision 1, Appendix 3 contributed by J. Hart & T.J. Schröder.


- Task 6.2.1: Modelling approach for hydraulic transport processes

- WP6.3: Radionuclide migration and uptake in the biosphere

The generic description for the transport and uptake of radionuclides in the biosphere, bioaccumulation, and dose conversion coefficients for relevant radionuclides that are used in the assessment are described in:

- WP6.3: Radionuclide migration and uptake in the biosphere


- Task 6.3.1: Modelling approach for transport & uptake processes

The aim of WP7 in the OPERA research plan was to establish all methods and tools to execute post-closure safety assessment calculations, perform these calculations and document the calculated results and the used methodologies.

- WP7: Scenario and performance assessment

The evaluation of all scenarios relevant for the post-closure safety assessment of a disposal facility in Boom Clay and the definition of the general outline of the features and resulting altered evolutions are described in:


- Task 7.1.1: Scenario development

The scenarios defined in report OPERA-PU-NRG7111 should have been translated into physical and geochemical representations to be used for the safety assessment. Some relevant processes have been defined through interviews with experts by selecting FEPs. The interviews and representations are described in the following report and excel-sheets:


- Task 7.1.2: Scenario representation

WP7.2: PA model development and parameterization

The evaluation of the fundamental processes behind radionuclide migration in Boom Clay and the resulting model description for the assessment are described in:


- Task 7.2.1: PA model for radionuclide migration in the Boom Clay

The formations surrounding Boom Clay are assumed to be aquifers. This task should include the modelling code that is used in the assessment to compute the transport of radionuclides from the host rock to Boom Clay. This modelling approach is described in OPERA-PU-DL362. In the following report, a generic description is presented of modelling aquifers:


- Task 7.2.2: PA model for radionuclide migration in the rock formations surrounding the host rock

The generic description for the transport and uptake of radionuclides in the biosphere, bioaccumulation, and dose conversion coefficients for relevant radionuclides that are used in the assessment are described in:


- Task 7.2.3: PA model for radionuclide migration and uptake in the biosphere

The definition of compartments and the parameters used for the scenario to be calculated for the assessment are described in:


- Task 7.2.4: Safety calculation

- Task 7.2.5: Parameterization of PA models

WP7.3: Safety assessment

The calculated results are compared with safety and performance criteria to allow to judge the safety and performance of the disposal facility. The process in defining the indicators is described in the following report:


- Task 7.3.1: Safety and Performance Indicators methodology

The several sources of uncertainty in a safety assessment are broadly categorized in three categories: scenario uncertainty, model uncertainty and data/parameter uncertainty. In OPERA, the solubility limits are considered as a model uncertainty and the impact of a variation in parameters used for the engineered barrier system and host rock are described in the following reports:


- Task 7.3.2: Definition of methods for the uncertainty analysis

The calculated results, an analysis and their comparison with safety indicators for a normal evolution scenario are described in:


APPENDIX 2: REQUIREMENTS IN THE DISPOSAL SYSTEM

Level 1: National and international requirements

The national and international requirements that provide a general orientation for long-term research programmes are derived from the relevant regulatory framework (IAEA, EU Euratom, ICRP) and national policy. The IAEA Safety Fundamentals constitute the basis on which to establish safety requirements for protection against ionizing radiation [IAEA, 2006a]. The 10 fundamental safety principles listed below should be satisfied in any activity. COVRA addresses all of these in its overall waste management programme. The present safety case most directly addresses principles 4 to 7, although Principles 1 to 3 are addressed in Chapter 1 of this report. Justification is normally applied not to waste management as such but rather to the nuclear activities that give rise to the radioactive wastes. Optimization will continue throughout the GDF development as understanding of the interactions between all system components grows. Limitation of risks is ensured by the dose limits described in section 3.1 and these limits are explicitly set to protect also individuals in the future. Principles 8, 9 and 10 are most relevant when the programme proceeds to the operational phase.

**IAEA Safety requirements specific for disposal**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Government responsibilities</th>
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<tbody>
<tr>
<td>Requirement 2</td>
<td>Responsibilities of the regulatory body</td>
</tr>
<tr>
<td>Requirement 3</td>
<td>Responsibilities of the operator (implementer)</td>
</tr>
<tr>
<td>Requirement 4</td>
<td>Importance of safety in the process of development and operation of a disposal facility</td>
</tr>
<tr>
<td>Requirement 5</td>
<td>Passive means for the safety of the disposal facility</td>
</tr>
<tr>
<td>Requirement 6</td>
<td>Understanding of a disposal facility and confidence in safety</td>
</tr>
<tr>
<td>Requirement 7</td>
<td>Multiple safety functions</td>
</tr>
<tr>
<td>Requirement 8</td>
<td>Containment of radioactive waste</td>
</tr>
<tr>
<td>Requirement 9</td>
<td>Isolation of radioactive waste</td>
</tr>
<tr>
<td>Requirement 10</td>
<td>Surveillance and control of passive safety features</td>
</tr>
</tbody>
</table>

Since 1984, the policy in the Netherlands is that all hazardous and radioactive waste must be isolated, controlled and monitored. [VROM, 1984: p.10; EA, 2014: p.12].

A single organisation has been established for management of all steps of the radioactive waste management process.

The policy in the Netherlands is that most of radioactive waste produced in the Netherlands is managed by a single organisation, namely COVRA. Transferal of the radioactive waste to COVRA includes transferal of the ownership and liabilities. COVRA is responsible for the management of the different interfaces and interdependencies between all steps of the radioactive waste management process [EA, 2014:p.21; VROM, 1984:p.4].

Radioactive waste is stored above ground for a period of at least 100 years.

Disposal is foreseen after interim storage above ground for a period of at least 100 years. In 1984, a decision-in-principle was taken to dispose of Dutch radioactive waste in a GDF. The policy in the Netherlands is that during the interim storage period the geological disposal programme is prepared financially, technically and socially in such a way that it can be implemented in practice. In all cases after 2130, a geological disposal route should become operational [EA, 2014:p.12; VROM, 1984:p.10; EZA, 2013:p.8].

In addition to a national GDF, the option of a multinational GDF is not excluded.

The option of sharing a GDF with one or more countries is also being considered in the Dutch ‘dual track’ policy in order to realise financial benefits through economies of scale [EA, 2014:p.20; EZA, 2013; EL&I, 2011: p.4-5]. A national research programme on geological disposal for radioactive waste is an essential element for both tracks of the policy [EU, 2011:p.53].

Radioactive waste is intended to be disposed of in a single, deep GDF, operating in 2130.

For the national disposal option, no separate facilities for Low and Intermediate Level Waste (LILW) and High Level Waste (HLW) are envisaged. Because of the relatively small waste volume expected to be collected in a period of 100 years, separate facilities are not expected to be feasible economically. Consequently, deep geological disposal will be required for most waste categories as a final solution [EA, 2014:p.17; EL&I, 2011:p.4].

The GDF has to be designed, operated and closed such that the process is reversible and the waste is retrievable.

In 1993 the government adopted, and presented to parliament, a position paper on the long-term underground disposal of radioactive and other high-hazard materials [VROM, 1993]. This forms the basis for further development of a national radioactive waste management disposal policy, which now requires that any GDF be designed in such a way that each step of the process is reversible.

Both rock salt and clay formations are considered as potential host rocks for geological disposal in the Netherlands.

Because the Netherlands has adopted the strategy of storage in dedicated surface facilities for at least 100 years, there is no immediate urgency to select a specific host rock. Both rock salt and clay formations would qualify, as potentially suitable host rocks for a geological disposal facility [EA, 2014:p.18; VROM, 2003:p.9].

Specific regulatory criteria for the siting or the performance of a GDF have not yet been defined.

There are general international guidelines (IAEA) on the siting and safety of GDFs. Furthermore, in principle the same radiation safety requirements that apply to the licensed nuclear facilities in the Netherlands would also apply to the GDF, at least during the operational phase.

The public has to be given the necessary opportunities to participate effectively in the decision-making process regarding radioactive waste.

Transparency is important to build confidence in the regulator, the implementer, and the safety of radioactive waste management routes, to enable a dialogue among stakeholders and/or public debate on geological disposal [EA, 2014:p.18]. Transparency should be ensured by providing effective public information and opportunities for all stakeholders concerned, including local authorities and the public, to participate in the decision-making processes in accordance with national and international obligations [EU, 2011:p.50].

Level 2: COVRA Strategic requirements

Strategic requirements of COVRA are derived from the objectives in its corporate documents. These requirements are constrained by the national and international requirements in the previous paragraph.

COVRA provides continuous care for radioactive waste in the Netherlands to protect people and the environment up to the time that a safe, stable situation is created, by the disposal of waste in a GDF.

During the period of long-term interim storage, it is important to develop and maintain knowledge about geological disposal by doing research. To assure financing across the whole chain and assess disposability of the waste processed and stored today, COVRA, therefore, coordinates and supports research on geological disposal; prepares disposal, including reserving and managing the financial means for its execution.

COVRA prefers simple, robust and proven designs of structures, systems and components to facilitate safe long-term operations. This applies also to designs of structures, systems and components of the GDF.

COVRA operates in an open and transparent manner.

COVRA communicates clearly and honestly with internal and external stakeholders about all its activities, including research, in a timely manner. COVRA serves as a Dutch knowledge centre for government, industry and society, including educational aspects and actively participates in various international settings in the field of radioactive waste management.

The disposal programme should take stock of available international knowledge.

The Belgian programme has developed extensive knowledge of disposal of radioactive waste in the Boom Clay since 1974. The Belgian programme includes an Underground Research Laboratory at Mol where experiments have been, and still are performed, to validate models. In 2010, COVRA signed a research and development agreement with the Belgian waste management organisation ONDRAF/NIRAS.

Other international collaborations in which COVRA participates in order to keep track of the necessary host rock specific research are the NEA Clay and Salt Clubs. COVRA is an active member of the working groups on a European Repository Development Organisation (ERDOWG) and on Natural Analogues, and participates in the Implementing Geological Disposal Technology Platform (IGD-TIP) of the EC. COVRA is also involved in European research projects that are suitable for countries that have only small amounts of nuclear power wastes, or that have no nuclear power but do have other radioactive wastes that need to be disposed of in a GDF.

10. The exceptions are radioactive waste with a half-life less than 100 days that is allowed to be toxic in the soils in which it is generated and large amounts of NORM waste that are disposed of (or reused) at designated landfill sites.

11. Spent research rector fuel is regarded as radioactive waste. For nuclear power plants, spent fuel is reprocessed in reactors between the producer of spent fuel and the ‘foreign’ reprocessing facility [EA, 2014: p.15].
Level 3: Strategic requirements of GDF

Strategic requirements of the implementer (COVRA) for safe emplacement and closure of the GDF are made on the basis of existing knowledge and understanding that aim to further define the requirements for a GDF in the Netherlands. These requirements will include items based on local and regional information meetings, e.g., during site investigations. Safety is provided by multiple safety functions.

The safety concept in the conceptualisation stage is the description of how the barriers in the disposal concept are integrated to provide safety after closure. Safety functions with assigned time frames are used for this description. A safety function is the action or role that a natural and/or engineered barrier performs after closure of the GDF to prevent radionuclides in the waste ever posing an unacceptable hazard to people or the environment. The necessary engineered barriers and systems should therefore ensure that they will not be penetrated during the thermal phase. In addition, the engineered barriers should not be able to be penetrated with present drilling technology should loss of information lead to inadvertent intrusion at an early stage in the post-closure life of the GDF. The safety barriers should also provide sufficient compartmentalisation in order to ensure that only a small part of the disposal facility is affected, in case of human intrusion. The description of the waste package envisaged for disposal is adopted from the Belgian waste management organisation and described in Chapter 4 and 6. IAEA safety requirement 8: Containment of radioactive waste [IAEA, 2011a: p.26] is covered by this strategic requirement.

The GDF will be constructed at sufficient depth to take into account the impact of surface phenomena. The host rock and geological environment should provide effective containment of the emplaced waste and isolation from the biosphere. The depth of the GDF should be sufficient to protect the facility from the effects of geomechanical processes such as erosion and glaciation during ice ages. In site investigations – to take place after several decades – any evidence of these processes will be evaluated. A surface phenomenon that might take place on a smaller time scale is flooding. Without maintenance of the infrastructure of dikes, more than half of the surface of the Netherlands would be flooded. Near-surface facilities for disposal of radioactive wastes of any kind are therefore not considered. In the conceptual stage, IAEA safety requirement 9: Isolation of radioactive waste [IAEA, 2011a: p.27-28] is covered by this strategic requirement.

The GDF will be constructed within a Tertiary Clay formation or Zechstein rock salt formation. The geological conditions in the Netherlands, with large salt formations in the Northern part of the country and clay formations at varying depth over the whole country, are in principle favourable from the perspective of disposal of radioactive waste (see e.g.: for clay, Bos, 2005:p.3; for rock salt, Storj, 1988:p.20). For OPERA, rock salt from the Zechstein formation and the Boom Clay from the Rupelian formation are considered as potential host rocks. OPERA has its main focus on the Boom Clay, as a large volume of information is already available on rock salt formations in the Netherlands. Waste types will be divided into groups to be emplaced in separate sections of the GDF.

Investigation of a generic disposal concept for all types of radioactive waste is one of main differences between OPERA and the previous European programmes. In OPERA, each considered only part of the waste inventory for disposal (mainly vitrified HLW).

The generic geological disposal concept investigated contains separate sections for each group of waste in a single facility in order to prevent or minimise the influence of the products generated by degradation of waste matrices and packages on other types of waste. In the case of heat-generating waste, the engineered barriers will be designed to contain the radionuclides for a period of several thousands of years, when the hazard potential of the wastes is highest (see Box 2.11). In this initial, so-called ‘thermal phase’ some of the HLW is still producing heat energy in amounts that could adversely affect the performance of the disposal system. The safety assessment is more robust if the waste package for these wastes completely contains the radionuclides for a period of a thousand to a few thousands of years, until the heat generation has decayed sufficiently. Engineered barriers should therefore ensure that they will not be penetrated during this thermal phase. In addition, the engineered barriers should not be able to be penetrated with present drilling technology should loss of information lead to inadvertent intrusion at an early stage in the post-closure life of the GDF. The safety barriers should also provide sufficient compartmentalisation in order to ensure that only a small part of the disposal facility is affected, in case of human intrusion. The description of the waste package envisaged for disposal is adopted from the Belgian waste management organisation and described in Chapter 4 and 6. IAEA safety requirement 8: Containment of radioactive waste [IAEA, 2011a: p.26] is covered by this strategic requirement.

The different disposal galleries and sections, and the geological disposal facility as a whole, will be closed (access routes backfilled and sealed) following a progressive, step-wise closure procedure.

The feasibility of post-closure retrieval of waste is required for a prolonged period, which has yet to be defined by the regulators – but it also has to be assured that any provision for retrievability does not have an unacceptable adverse effect on safety or performance. Leaving the access to the disposal areas open for long times is therefore unacceptable, since the most effective barrier between the wastes and the biosphere is achieved by closing and sealing the GDF as soon as practically possible, following the emplacement of waste. A possible compromise that takes both objectives into consideration is in progress, step-wise closure procedure that leaves some emplaced wastes more easily retrievable for some time, while retrieval of others in backfilled sections would require substantial clay effort. The description of closure of disposal galleries, disposal sections, shafts and ramps is described in Chapter 4. IAEA safety requirement 5: - Passive means for the safety of the disposal facility [IAEA, 2011a:p.21-22] is intended to be partly covered by this strategic requirement.

Geological disposal planning assumes that surveillance and monitoring will continue for as long as deemed necessary.

Post-closure surveillance and monitoring is assumed to be continued until adequate confidence has been obtained concerning the safety of the geological disposal of waste. It important to understand, however, that the post-closure performance and safety does not depend in any way on the ability to continue monitoring.

Level 4: Requirements on system components

In Chapters 5 and 6, the safety functions of the individual system components are described and, for some of these, specific performance requirements are proposed. During later work, further safety related requirements on individual components may be developed. Examples might be requirements for the mechanical strength of overpacks, waste matrices and tunnel liners or for the leachability of HLW wastes. It should be noted, however, that the overall disposal system is composed of multiple barriers that are partly independent and partly overlapping and are intended to work in an integrated fashion. This implies that a judgement on the acceptability of the repository system cannot be based on the performance of any single barrier. In practice, the most common application of developing component-specific requirement is use in the design processes that lead to a preferred total system concept.

The COVRA preference is for using shielded wastes packages that minimise operation and consequent operational radiation doses in the underground.

In the Boom Clay GDF concept, shielded disposal packages that can be contact-handled are foreseen in order to minimise operations and to make handling of waste packages in the underground easier. It is also expected that the retrieval of these shielded waste packages can better be demonstrated than retrieval of unshielded wastes. In the rock salt disposal concept, the shielding in the HLW disposal package is removed after emplacement of waste. There are preferences for materials and implementation procedures for which broad experience and knowledge already exists.

The ability to show that adequate levels of containment and isolation are provided over the necessary long time frames requires that the disposal concepts are robust with respect to potentially perturbing phenomena and to uncertainties that may arise owing to the long time frames involved. Thus, as far as reasonably possible, events and processes that could be detrimental to isolation and containment, as well as sources of uncertainty that would hamper the evaluation of how the systems evolve over time, are avoided or reduced in magnitude, likelihood or impact by means of siting or design choices. In general, the introduction of foreign or non-natural material into the GDF can lead to difficulties with the prediction of possible effects of these materials on the host rock and/or other EBS materials and thus can increase uncertainties.

Similarly the processes and procedures for the development, construction and operation of the GDF need to be robust, i.e., simple, reliable and effective. Therefore, there is a preference for above ground construction, assemblage and quality assurance of waste packages and for the use of technologies that have been proven in related fields of work, such as mining, tunnel construction (concrete support) and the oil and gas extraction industry. Complementary safety-related criteria will be used to enhance understanding of the calculated post-closure evolution of the disposal system.

Criteria are used to compare calculated results of an assessment with pre-defined limits or targets or with comparable natural processes. The common radiation protection criteria are dose limits and risk constraints. These overarching safety criteria are used to judge the potential future impacts of the total disposal system. Criteria complementary to dose and risk can be used to assess the calculated performance of specific components of the disposal system. A further perspective on the potential impacts of radionuclides released from a repository can be obtained by comparisons with natural radioactivity in the environment.

Knowledge of the distribution of naturally occurring radionuclides in the Netherlands and sufficient understanding of how these radionuclides enter and move within the accessible biosphere can be used to enhance confidence in the models employed in calculations of the potential migration of radionuclides from the disposal facility. To account for the fact that not all of the radionuclides in the repository occur naturally, the radioactivity (rather than the radioactivity of calculated releases) can be compared with the radioactivity of the radionuclide flows in nature. Such an approach has been used in Switzerland; ordinary natural radioactivity fluxes are several multiples larger than the expected radioactivity flux from the Swiss GDF [NAGRA, 2002]. IAEA safety requirement 6: Understanding of a disposal facility and confidence in its safety [IAEA, 2011a:p.22-23] is intended to be enhanced by choosing criteria that require sufficient knowledge of the mobility of naturally occurring radionuclides and chemical analogues for artificial radionuclides.
APPENDIX 3: Comparison of the OPERA and CORA

Disposal concept
The goal is to progressively refine the disposal concept in suc-
cessive research programmes over the next decades. To do so, it
is important to identify the similarities and differences between
the previous research programme CORA (1995-2001) and OPERA
(2011-2017). The refinement can be based on the available expe-
rience and knowledge. In both programmes, a generic, that is
site-specific, disposal facility in Boom Clay at a depth of 500 metres
within a thickness of clay of 100 metres has been investigated.
Both programmes are connected to the underground facili-
ty at 500 metres depth are envisaged.

Experience and knowledge available
Tunnels in poorly indurated clay have been constructed in the
Netherlands for example Westerschelde (1992-1993). These tunnels
demonstrate the possibility to build underground structures and
to provide experience with the potential degradation of concrete
in poorly indurated clay. Traffic tunnels have a larger diameter than
envisaged for the disposal facility and can be located at several
metres depth under ground. The underground research laboratory
HADES is connected to the Earth's surface with shafts. It progressively provides the demonstration of building and operating a geological disposal facility in this low strength rock. The progress made in Belgium is used to provide some understand-
ing in the choices made between both programmes.

Construction
Available knowledge
In the underground research laboratory Mol, support against
convergence was manually made with a cast iron lining in the first
section. In next sections, concrete support was manually installed.
From 1980-1984, the clay was frozen for excavation and installa-
tion of the support. In 1987, a technique was developed to excavate
Boom Clay without the need to freeze. Un-reinforced concrete
blocks were installed semi-manually. From 2001-2002, a connect-
ing gallery was made with tunnel boring machines and the concrete
segments were automatically installed using the wedge-block
system. Outside and inside diameters are 4.8 and 4.0 metre. In the
period 2006-2007, an experimental gallery was made perpen-
dicular on the connecting gallery. The construction of this gallery
was started from the inside of the connecting gallery. An industrial
architecture to make these crossings was achieved. The outside and
inside diameters of this experimental gallery are 2.5 and 1.9 metre.

Proposed methodologies
In both programmes, CORA and OPERA, galleries for transport
are excavated with tunnel boring machines and supported with a con-
crete lining. There are differences in the methodology to construct the
empty volume to emplace the waste packages.

In CORA:
• TRUCK-I: disposal galleries are constructed with the
  same technique as transport galleries. To allow
  men to access the tunnel, a concrete supported
disposal gallery with an inner diameter of 2.2
  metre and outer diameter of 3.3 metre was proposed.
  The disposal galleries are connected with secondary galleries with an outer
diameter of 4.6 metre and inside diameter of 3.5 metre. Primary
  galleries are the main transport roads and connected to the shafts and secondary
  galleries. Primary galleries have the same dimensions as the
  secondary galleries [Van de Steen, 1998];
• TRUCK-II, a lining with a length of 5 metre and
diameter of 0.75 metre is pushed from the inside
  of a secondary gallery. The concrete supported
  outside diameter of the primary and secondary
  gallery was the same. It was proposed to be 6
  metre to push the 5 metre lining. The disposal
  cell was envisaged to hold one waste container.
  The aim of this methodology was to reduce
  excavation and the alkaline condition of the plastic
deposition in Boom Clay [Barnichon, 2000].

In OPERA, a concrete lining for the disposal galleries is envisaged
with the same technique as constructing the transport galleries. The disposal galleries have an inner
diameter of 2.2 metre for HLW to emplace contact-
handled waste packages. Several waste containers are
proposed to be emplaced in each disposal gallery. For the
cost-estimate, the disposal galleries are constructed from
the inside of the transport galleries. This building
methodology has been demonstrated to require the outer
diameter of the disposal gallery to be half of the outer
diameter of the transport gallery and therefore crossings
are preferred to be limited. If the outside diameter is
chosen to be 3.2 metre, then consequently the outside
diameter of the transport gallery should be 6.4 metre.
In CORA, the construction of the disposal galleries is envisaged
to take place when also the waste packages are
emplaced. For safety, a physical separation in the
underground facility between excavation and emplace-
ment was automatically installed using the wedge-block
system. Outside and inside diameters are 4.8 and 4.0 metre. In the
period 2006-2007, an experimental gallery was made perpen-
dicular on the connecting gallery. The construction of this gallery
was started from the inside of the connecting gallery. An industrial
architecture to make these crossings was achieved. The outside and
inside diameters of this experimental gallery are 2.5 and 1.9 metre.

Operation
Available knowledge
In the Belgium programme, in 2004, an additional waste package
disposal for HLW was envisaged to prevent contact between
pore water and waste form for the period that waste emits heat till
such an extent that the influence of temperature on the hydraulic,
mechanical and chemical properties of the host rock need to be
taken into account. In the developed supercontainer concept, the
concrete based overpack and the tube of the concrete buffer can
prevent this contact i.e. the potential migration of radionuclides in
the host rock can be calculated with temperature

independent properties. The carbon steel overpack is assumed to
provide mechanical resistance against the underground pressure.
An additional benefit of this supercontainer concept is that the
concrete buffer provides sufficient shielding against the ionising
radiation of the waste.

Proposed methodologies
In CORA, remote-handled waste packages were envisaged to be
emplaced with a transport vehicle and a transport container.
Two methodologies were suggested to provide mechanical
means to the underground pressure and be corrosion-
resistant [Barnichon, 2000: p.91/92].
1. A stainless steel lining in the disposal cell;
2. A stainless steel overpack surrounding the waste container.
The waste container or overpacked waste container is transferred
from the disposal gallery to the transport gallery. The transport
system should provide shielding during this transference. A telescopic
arm is used to replace the waste container or overpacked waste
container. The diameter of the disposal entries, backfill as well as
waste containers, are not larger than 0.75 metre and the weight is
less than 1000 kg. The left empty volume surrounding the c
container was envisaged to be backfilled with sand to facilitate
retrieval of the waste package. Cement based materials were not
advised because it was thought that highly alkaline fluids would
be released and would increase the dissolution rate of vitrified
waste. Prefabricated blocks were positioned in front of the container
for protection. To prevent the corrosion, a steel plate is placed in
front of the disposal cell to provide sealing.

In OPERA contact-handled waste packages are envisaged to be
emplaced in order to minimise operations in the underground
facility. Each waste package can have a diameter of 0.7 metre and
a weight of 24000 kg. For the cost estimate, the supercontainers are
loaded on a transport cart and transported with a battery-driven
locomotive to the disposal gallery. The cart has a hydraulic lift
system which keeps the cart in a raised position. Once the
transport cart arrives at the disposal position, the cart is lowered so
that the supercontainer rests on the floor structure. Several super-
containers are envisaged to be disposed in one disposal gallery.
The empty volume left is backfilled with foamed concrete.
This concrete can have a compressive strength of at least 30
MPa and a linear expansion rate up to 5×10⁻⁶/°C. The potenti-
mal damage to the waste package when retrieved is expected to be
negligible. Sealing is suggested to be performed with a prefabricated block
of concrete. The supercontainer rests on the floor structure. At the position where
this clay is positioned, a section of the concrete liner may need to be
removed for the post-closure safety in order to prevent the
presence of interfaces along which radionuclides can potentially
easily migrate.

In both research programmes, the transport galleries are left open
for a certain period to facilitate retrieval of waste packages.

Waste
In CORA only vitrified waste from the reprocessing of spent nuclear
power fuel is assessed. In OPERA, almost all types of waste should be
or to be stored at CORA's premises have been identified. The
waste is collected in nine waste containers with the same origin,
and have identical or closely related conditioning character-
istics. Each waste container should be sufficiently characterised for a
post-closure assessment. These are:
1. Vitrified waste from the reprocessing of spent nuclear
power fuel;
2. spent research reactor fuel;
3. compacted waste from the reprocessing of spent
nuclear power fuel;
4. legacy waste;
5. depleted uranium;
6. processed molybdenum waste;
7. spent ion exchange resins processed with sludge;
8. compacted waste processed at COVRA's premises.

In both research programmes, the evolution of engineered
barriers is not taken into account i.e. the radionuclides in the waste
are released in Boom Clay as a function of the solubility limit of the
elements. The transport of radionuclides is assumed to take place
by diffusion.

Boon Clay
Kd values
Cations and cation-complexes can be retarded by the slightly
negatively charged clay mineral surfaces. Another retardation
process is ultratitration. A larger retardation coefficient
 corresponds to a larger contamination time in Boom Clay.
The following table shows the Kd values and diffusion
accessible porosity (η). The Kd values used in CORA [Grupa, 2000:
p.527] most resemble the coefficients supplied by SCK-CEN in the
EURATOM project Spent fuel disposal Performance Assessment
(SPA project) [Baudoin, 2000]. In OPERA, coefficients have become
available that are supported by experiments in Boom Clay in Mol.
These Kd values are usually larger than the values used in CORA.
The diffusion accessible porosity for each cation or cation-complex is treated separately from the Kd value in OPERA. Many of experimental supported Kd values have the same range in values. In the Belgium programme, representative elements for cations (alkali and earth-alkaline metals) and cation-complexes are assigned [ONDRAF/NIRAS, 2013: p.108, 111]. These elements are underlined in the table above. Complexes with natural organic matter are the usual cation-complexes.

<table>
<thead>
<tr>
<th>Element</th>
<th>CORA</th>
<th>OPERA</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPK-project [Bauedon, 2000]</td>
<td>[Gnepp, 2000: Corr-3-41]</td>
<td>[Schneider, 2017: HBG/6123]</td>
</tr>
<tr>
<td>Ni(II)</td>
<td>SOGEN</td>
<td>Kd [L/kg] calculated for Mol</td>
</tr>
<tr>
<td></td>
<td></td>
<td>for Mol</td>
</tr>
<tr>
<td></td>
<td></td>
<td>η</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[Kd [L/kg]]</td>
</tr>
<tr>
<td>Am</td>
<td>600</td>
<td>0.35</td>
</tr>
<tr>
<td>Ca</td>
<td>20</td>
<td>0.35</td>
</tr>
<tr>
<td>Cs</td>
<td>500</td>
<td>0.35</td>
</tr>
<tr>
<td>Co</td>
<td>600</td>
<td>0.35</td>
</tr>
<tr>
<td>Cr</td>
<td>1000</td>
<td>0.13</td>
</tr>
<tr>
<td>Eu</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Np</td>
<td>300</td>
<td>0.35</td>
</tr>
<tr>
<td>Ni</td>
<td>50</td>
<td>0.35</td>
</tr>
<tr>
<td>Nb</td>
<td>50</td>
<td>0.1</td>
</tr>
<tr>
<td>Pd</td>
<td>50</td>
<td>0.1</td>
</tr>
<tr>
<td>Pu</td>
<td>1500</td>
<td>0.35</td>
</tr>
<tr>
<td>Pa</td>
<td>200</td>
<td>0.35</td>
</tr>
<tr>
<td>Ra</td>
<td>50</td>
<td>0.1</td>
</tr>
<tr>
<td>Rb</td>
<td>200</td>
<td>0.35</td>
</tr>
<tr>
<td>Sm</td>
<td>100</td>
<td>0.1</td>
</tr>
<tr>
<td>Sn</td>
<td>100</td>
<td>0.1</td>
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<tr>
<td>Sr</td>
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<td>0.35</td>
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<tr>
<td>Tc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Te</td>
<td>150</td>
<td>0.35</td>
</tr>
<tr>
<td>Th</td>
<td>300</td>
<td>0.35</td>
</tr>
<tr>
<td>U</td>
<td>2000</td>
<td>0.1</td>
</tr>
<tr>
<td>Zr</td>
<td>200</td>
<td>0.1</td>
</tr>
</tbody>
</table>

APPENDIX 4: OPLA and CORA

Disposal concept
The goal is to progressively refine the disposal concept in successive research programmes over the next decades. To do so, it is important to identify the similarities and differences between the past and the present and understand how these developed over time. In OPERA, there was a focus for research in Boom Clay since the research for a GDF in rock salt has been investigated since the seventies of the previous century. There is a variation in the point of departures for the disposal concepts:

- Before OPLA, objective was to study the possibility of disposing radioactive waste in a dome in rock salt. COVRA was not established, seabed disposal for LLW took place and the disposal concept for a waste inventory for 3500 MWe CSD-v was envisaged i.e. expanding nuclear power with 3000 MWe. Spent Research Reactor Fuel was sent to the USA and therefore not included in the disposal concept. The CSD-v were not yet produced and the diameter for the canisters used in this study are smaller than the actual CSD-v stored nowadays at COVRA’s premises.
- Geological formation: domal salt
- Top of dome at least 250 metre at depth;
- Facility surrounded by at least 200 metre rock salt;
- Disposal depth of High Level Waste 800 metre;
- Vertical disposal galleries till 300 metre in length with a concreted steel liner;

- OPLA (1982-1992): objective was to study the possibility of radioactive waste for three different nuclear power scenarios.
- Facility in domal salt or bedded salt
- Boroholes with a length of 2000-2500 metre in domal salt
- CORA (1995-2001): disposal of reprocessed nuclear power waste products (CSD-v) was investigated.
- Facility in domal salt or bedded salt
- Boroholes with a length of 2000-2500 metre in domal salt
- Facility surrounded by at least 200 metre rock salt;
- Disposal depth 800 metre
- Short disposal galleries to disposal 1 CSD-v (one vHLW canister)

Experience and knowledge available
As described in Chapter 2, the Waste Isolation Pilot Plant in the U.S.A. has been licensed to receive radioactive waste since 1999. The open volumes in this disposal facility in bedded salt are excavated using road headers and the excavated volumes for disposal are supported by bolts. In the Netherlands, there are open volumes generated in rock salt domes to explore salt by dissolution. The control of the open volume to be generated and stabilization of the open volume is less with dissolution mining. In the Waste Isolation Pilot plant contact-handled waste is emplaced and bags of MgO are used to control the chemistry in case of potential radionuclide release.

Construction
The research programme for disposal on Land is the Dutch acronym OPberging te Land (OPLA). The research period was from 1982-1992. Also in CORA (1995-2001), disposal concepts in rock salt were investigated. The description of the construction methodology is limited to ‘conventional mining techniques’ without further specification. In the research before OPLA, the construction methodology is switched from excavation by dissolution drilling to dry drilling in order to limit corrosion of the drilling equipment [Hamstra, 1981 & Hamstra, 1995].

Operation
Unshielded HLW waste packages were envisaged to be emplaced in the underground before OPLA, within OPLA and in CORA. Before 1982 and in OPLA, for borehole disposal, the canisters were lowered by a wire or by free fall. In case of free fall, the relative annulus between the canister and wall of the hole compresses the air below the canister and slows its fall. Notwithstanding this, the special precautions were foreseen to minimize the effect of the impact, either an amount of salt between each canister or a loose deformable head that would convert the kinetic energy of the canister into deformation of the head [Hamstra, 1981 & 1985]. In OPLA, the borehole was filled with brine to reduce the impact of fall [OPLA, 1989 & 1993]. The Dutch government introduced the concept of retrievability of the waste to have human control over the emplacement of waste packages [VROM, 1993: p.7]. In the previous research programme CORA, the waste container or over-packed waste container is transferred from the transport container into the disposal cell. A shutter system should provide shielding during this transferral. A telescopic arm is used to emplace the waste container or over-packed waste container. The diameter of the disposal entities, backfill as well as waste containers, are not larger than 0.75 metre and the weight is less than 1000 kg. The left empty volume surrounding the container was envisaged to be backfilled with sand to facilitate retrieval of the waste package. The start of the retrieval of waste is the removal of the backfill. The Dutch government was convinced that the retrievability of waste was technically possible with this disposal concept [VROM, 2002: p.12].

Closure
In OPLA, the brine is suggested to be removed from the borehole and closure was envisaged by creep of the salt [OPLA, 1989 & 1993]. The Dutch government introduced the concept of retrievability of the waste to have human control over the closure of the facility [VROM, 1993: p.7].
## APPENDIX 5: Radionuclide inventory of each waste group at the expected time of disposal

### Table A-1: Activity per radionuclide per waste family aggregated waste family in Bq

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Activity (Bq)</th>
<th>CSD-v</th>
<th>SRRF</th>
<th>CSD-c</th>
<th>Legacy Waste</th>
<th>LILW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ac-227</td>
<td>2.90E+05</td>
<td></td>
<td>3.64E+01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ag-108m</td>
<td>9.79E+05</td>
<td>1.29E+04</td>
<td></td>
<td>1.30E+12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Am-241</td>
<td>5.04E+16</td>
<td>1.69E+15</td>
<td>3.20E+13</td>
<td>4.87E+11</td>
<td>2.10E+13</td>
<td></td>
</tr>
<tr>
<td>Am-242m</td>
<td>7.45E+14</td>
<td>0.00E+00</td>
<td>9.36E+10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Am-243</td>
<td>1.23E+15</td>
<td>4.31E+12</td>
<td>3.56E+11</td>
<td>1.32E+10</td>
<td>6.35E+09</td>
<td></td>
</tr>
<tr>
<td>Ba-133</td>
<td></td>
<td></td>
<td>2.55E+06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Be-10</td>
<td></td>
<td></td>
<td>2.83E+09</td>
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<tr>
<td>Br-197</td>
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<td></td>
<td>4.77E+07</td>
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<td>C-14</td>
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<td></td>
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<tr>
<td>Cd-113m</td>
<td>9.63E+09</td>
<td></td>
<td>2.03E+11</td>
<td>3.30E+10</td>
<td>1.80E+10</td>
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<tr>
<td>Cf-249</td>
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<td>1.85E+07</td>
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<tr>
<td>Cf-251</td>
<td>7.74E-08</td>
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<tr>
<td>Cs-133</td>
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<td>Cs-134</td>
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<td>8.27E+12</td>
<td>1.18E+10</td>
<td>7.58E+09</td>
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<td>Cs-135</td>
<td>1.39E+12</td>
<td>1.81E+10</td>
<td>6.51E+09</td>
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<td>Cs-138m</td>
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<td>Cs-139</td>
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</tr>
<tr>
<td>Cs-140</td>
<td>1.58E+17</td>
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<td>5.33E+10</td>
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<td>surface</td>
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<td>1.56E+08</td>
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<td>5.93E+08</td>
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<td>&lt; 1 Bq</td>
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<td>neutron cap</td>
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<td>10,000 × compacted waste</td>
<td>1.27E+07</td>
<td>max batch 24 containers</td>
<td>surface</td>
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<td>2.21E+12</td>
<td>typical [AREVA, 2007]</td>
<td>1.38E+10</td>
<td>max guaranteed [AREVA, 2011]</td>
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<tr>
<td><strong>Cs-139</strong></td>
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<td>1.09E+07</td>
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<td>4.77E+06</td>
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<td>1.62E+02</td>
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<td>1.04E+09</td>
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<td>3.25E+12</td>
<td>max guaranteed [AREVA, 2001]</td>
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<td>neutron cap</td>
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<td><strong>Eu-152 m</strong></td>
<td>secondary waste stream</td>
<td>9.96E+09</td>
<td>max batch 24 containers</td>
<td>surface</td>
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<td><strong>H-3</strong></td>
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<td><strong>U-232</strong></td>
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<td>10,000 × compacted waste</td>
<td>2.95E+05</td>
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<td>3.20E+02</td>
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<td>3.06E+06</td>
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<td>1.25E+06</td>
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<td><strong>U-236</strong></td>
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<td>max weight and isotopic</td>
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<td>5.53E+07</td>
<td>max weight and isotopic</td>
<td>1.88E+07</td>
<td>max batch 24 containers</td>
<td>surface</td>
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<td><strong>U-239</strong></td>
<td>1.05E+11</td>
<td>max batch 28 containers</td>
<td>8.91E+09</td>
<td>max batch 24 containers</td>
<td>mainly neutron cap</td>
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Table A-3: Activity per COGEMA waste container after 130 years decay from production

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<th>Spent Low Enriched Uranium Fuel</th>
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<td>1.03E+12</td>
<td>[Dodd,2000]</td>
</tr>
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<td>2.18E+09</td>
<td>[Dodd,2000]</td>
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<td>Ba-133</td>
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<td>Bi-207</td>
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<td>Bi-214</td>
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<td>[Dodd,2000]</td>
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<td>Cs-138</td>
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<td>Cd-113 m</td>
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<td>Cs-137 (one month), 1.310%</td>
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Table A-4: Activity per ECN container with uranium collection filter and legacy waste after 130 years decay from cooling

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<td>Nb-94 compacted waste</td>
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<td>1.17E+05</td>
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Table A-5: Activity per 200 litre drum processed molybdenum waste (200 litre drums contained in 1000 litre concrete containers) 130 years after collecting the waste

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This report 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 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.