LONG-TERM RESEARCH PROGRAMME

FOR GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE

Overall research programme and work programme for 2020-2025

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This document was prepared by COVRA in collaboration with Technopolis Group and advised by two international advisors during Winter 2019-2020.
Authors:

COVRA
Ewoud Verhoef
Erika Neeft
Jeroen Bartol
Marja Vuorio

Technopolis Group
Chiel Scholten
Alexander Buitenhuis
Geert van der Veen

International advisors
Neil Chapman
Charles McCombie

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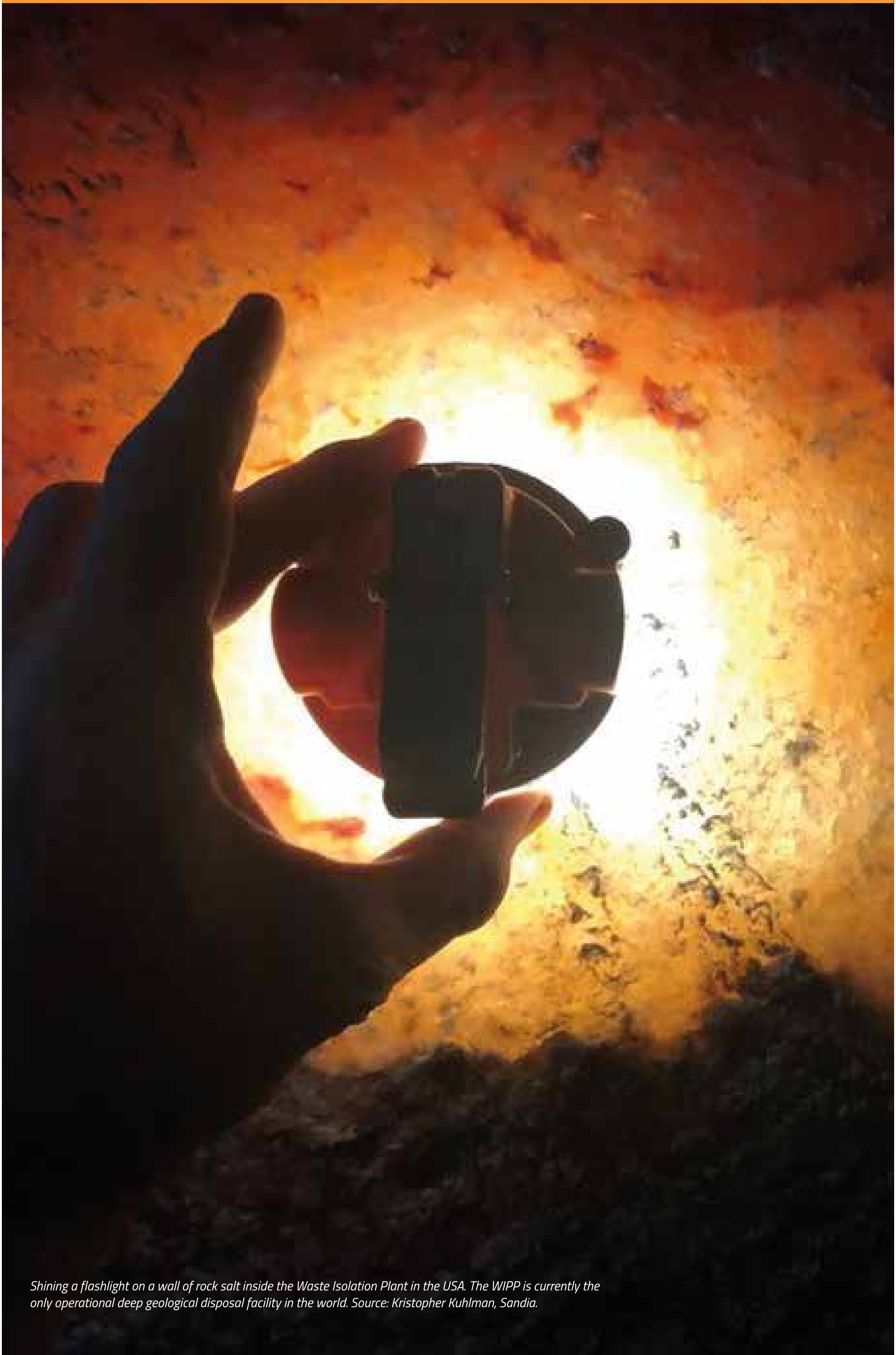
Contents



Shining a flashlight on a wall of rock salt inside the Waste Isolation Plant in the USA. The WIPP is currently the only operational deep geological disposal facility in the world. Source: Kristopher Kuhlman, Sandia.

Foreword

When visiting COVRA in the province of Zeeland, the storage buildings for radioactive waste may look like they have been carved out of solid rock and can last forever. But don't let the appearances fool you: the storage of radioactive waste at COVRA is only a temporary solution. The buildings have been designed for 'just' a century or two. After this period, a large part of the waste is still radioactive. With the current state of science and technology, disposal of this long-lived waste in stable geological layers in the deep underground is the only accepted solution to ensure that the waste will still remain out of the human living environment after thousands of years. This is called deep geological disposal.

For long-term management, COVRA must align its services with the changing market, which constantly offers different types and quantities of radioactive waste. Because COVRA is responsible for the entire waste management chain, we can take the requirements for the geological disposal of radioactive waste into account already when collecting and processing it. Conversely, we can only acquire now the information and knowledge we need to properly carry out the future disposal. To balance the short and long-term interests and knowledge of both predisposal and disposal activities, we need a robust and consistent knowledge management. An essential part of the knowledge management is an active, continuous research programme on geological disposal.

According to Dutch policy, the definitive decision on the disposal method will be taken around 2100 and start of disposal is expected around 2130. This provides us time to learn from experiences in other countries, to carry out research and to accumulate the knowledge to make well-founded decisions. To develop the necessary knowledge 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, Boom Clay and Ypresian Clay), potential GDF design options, the post-closure performance, and level of the public confidence and acceptability.
2. **Assess the disposability 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. **Assure adequate funding for disposal, based on regularly updated cost estimates for the GDF:** identifying and where possible optimising cost-determining features of a GDF.

In this document we explain how the long-term research programme will look like. How it builds on the OPERA safety case from the previous research programme and uses a structured process to select research activities to be carried out over the coming years. You can also find a detailed plan for the research in the coming five years (2020-2025). You can read how these activities will strengthen COVRA's competences in scientific and technical areas related to geological disposal. How we plan to inform politicians, the public and the scientific/technical community about the progress of geological disposal in the Netherlands. The plan is not yet carved in stone and will evolve over time.

Dr. ir. Ewoud Verhoef
Deputy Director COVRA

A tunnel within the Waste Isolation Plant (USA), a geological disposal facility in rock salt, that is expanded using a drum miner. Source: Kristopher Kuhlman, Sandia.

The new geological disposal research programme: what are its goals and objectives?

1. Introduction

COVRA's long-term research programme is set up and financed by COVRA as a follow-up for the previous research programme OPERA. The activities within the research programme will be carried out by COVRA and Dutch research organisations, and in collaborative projects with foreign (research) partners. In this chapter we introduce the long-term research programme and its rationale.

1.1 Background of the programme

In the Netherlands radioactive waste is produced by power generation, industry, hospitals and research organisations. Radioactive waste is waste that generates ionising radiation which can be harmful to living tissue, including humans; it should therefore be isolated from the environment until the radiation level has sufficiently decayed. To that end, all Dutch radioactive waste is isolated, processed, safely stored and controlled at COVRA (Centrale Organisatie voor Radioactief Afval) in Zeeland. At COVRA all Dutch radioactive waste is stored above ground for at least 100 years. After this period, around 2130, the radioactive waste should be disposed underground in a safe geological disposal facility (GDF). COVRA is responsible for preparing and realisation this geological disposal of radioactive waste.

In order to develop a safe GDF in the Dutch subsurface, information of the behaviour of radionuclides, the processing of waste, engineered barrier systems, evolution of the host rocks and the construction of a GDF is needed. The internationally accepted method for presenting this information is by means of a safety case. In a safety case all technical-scientific information about the design and safety of a GDF is collected. It contains a quantitative safety assessment and all technical-scientific arguments that support the safety assessment. A safety case is used for ensuring optimised and disposal compatible processes throughout the radioactive waste chain by COVRA and is used for decision-making about geological disposal by the government.

The Netherlands considers both a national as well as a shared repository option (dual track). The long-term research programme should provide valuable scientific and technical information for the decision-making on and preparation of a national or multinational GDF for the Dutch radioactive waste. This information is obtained through research activities that are synthesised into a safety case. The focus of the research programme will be on both types of geological media in the Netherlands that are considered suitable for the disposal of radioactive waste (i.e. host rocks): rock salt and poorly indurated clays. Some research is done in collaboration with European waste management organisations (WMOs). Also, this work benefits the national research programme.

1.2 Need for a programme

There is an operational need for research by COVRA. The research is instrumental to develop and optimise current processes in radioactive waste management that are suitable for future geological disposal. This also affects the waste handling throughout the waste supply chain. The research programme also provides insights into the costs that are associated with geological disposal.

The Netherlands is obligated by the European Commission to develop periodically a national programme for radioactive waste (NPRA) which includes research on geological disposal of radioactive waste (I&W 2016). COVRA supports this obligation with the current research programme, which provides recent information to the NPRA and contributes to decision-making by the government.

In Europe, many countries that have (high-level and long-lived) radioactive waste are studying geological disposal. With its research programme, the Netherlands can collaborate with other countries and efficiently acquire knowledge developed abroad and can actively participate in several international bodies on geological disposal.

A long-term research programme is especially important now, as several other countries are making crucial progress towards the realisation of geological disposal facilities (cf. Figure 1 for developments in Europe). This provides a unique window of opportunity to efficiently learn from other countries and to incorporate their results into the research and plans for geological disposal in the Netherlands.

The research programme is important for sustaining and strengthening the nuclear knowledge infrastructure in the Netherlands. In 30 years, most of the nuclear facilities and organisations in the Netherlands are planned to close or reduce their activities while currently only new facility is foreseen (the Pallas reactor). The number of people that have experience in the nuclear sector and with radioactive waste will then reduce. The long-term research programme is therefore needed to maintain sufficient knowledge about radioactive waste (handling) in the Netherlands for the future. Similar knowledge issues may also arise in geological exploration and mining in the Netherlands, as in the long-term oil and gas activities in the Netherlands may be reduced due to the ongoing energy transition – although geothermal exploration may fill this gap.

1.3 Mission of the programme

COVRA has the responsibility to prepare the construction of a safe geological disposal facility for radioactive waste before 2130. This can be either a national GDF or an international shared GDF - both routes are left open. In both cases, COVRA needs to continuously acquire knowledge and build capacity through scientific and technological research.

Knowledge about the future GDF has also impact on the operations of COVRA. It indicates the costs that COVRA must reserve for the

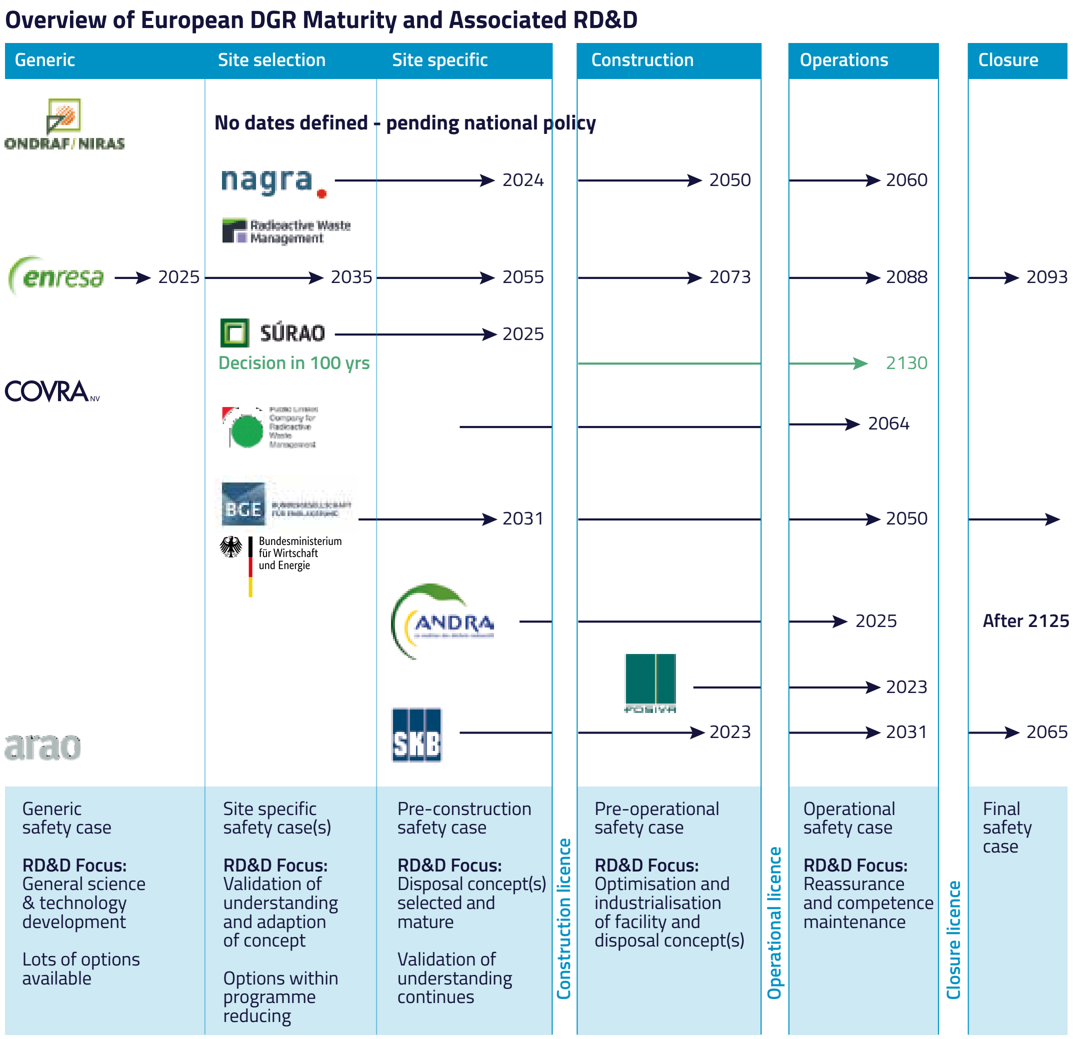


Figure 1: Overview of European Deep Geological Repository Maturity and Associated RD&D (IGD-TP 2018)

construction of the GDF and it determines how current waste is efficiently processed in order to be safely disposed in the GDF. The latter is called disposability. Knowledge acquisition on the geological disposal of radioactive waste is essential for COVRA. Therefore, COVRA has decided to build on its R&D work to date and set up a long-term structured research programme that will run for 30 years up to 2050. This planned approach guarantees continuity and can contribute to a strengthened nuclear knowledge infrastructure in the Netherlands, particularly regarding radioactive waste disposal.

Three major periods are characterised in the coming 90 years that are covered by the long-term research:

- The first period lasts from **2020 until 2030**. In this period most industrial parties in the Dutch nuclear sector remain active. This means that the industrial process knowledge remains, and therefore is to a large extent accessible. It is essential to incorporate this knowledge of industrial waste management as much as possible and this should be done in the ten years to come.
- The second period lasts from **2030 until 2050**. During this period the nuclear landscape in the Netherlands will most likely change in the sense that almost all existing nuclear reactors are planned to be decommissioned in the Netherlands. Three Dutch reactors will be dismantled. When these reactors are dismantled it is important to have a research programme, since parts of the dismantled reactors will have to be processed to be placed in the geological disposal facility. One new nuclear reactor is currently foreseen, the Pallas reactor for medical isotopes production.
- The third period lasts from **2030 until 2050.** During this period COVRA will work on updating generic safety cases or poorly indurated clays and rock salt as host rocks. The research done within the programme is both fundamental and applied. Through the research programme COVRA is prepared for this decision-making. In the meantime, generic safety cases are periodically updated to include developments and new insights. In 2100, assuming no multinational repository project has been implemented, there will ultimately be one or more detailed safety cases used to locate and construct a geological final repository in the Netherlands.

The long-term research programme will not only strengthen the national research infrastructure, but it will also enable Dutch researchers to participate in international knowledge platforms. Given the research developments abroad (as discussed in the previous section), the importance to stay well connected and learn from the experienced countries increases. Especially since major steps are expected be taken in the development of techniques for the construction of GDFs. Valuable learning opportunities will occur since Finland, Sweden and France will have started the construction/operation of their final disposal facilities well before 2050.

1.4 Goal and objectives

The main goal of the long-term research programme is:
To develop knowledge for implementing safe and efficient geological disposal of radioactive waste in poorly indurated clays and rock salt in the Dutch subsoil taking into account both the begin and end of the radioactive waste chain.

The main goal of the programme is supported by three driving forces that contain more specific objectives:

1. Increasing technical and societal confidence in feasible, long-term and safe disposal of radioactive waste in the Dutch subsoil. Thereby supporting the requirements of the EC Waste Directive.
2. Improving cost estimates by reducing uncertainties and optimising costs for the realisation and exploitation of a geological disposal facility for radioactive waste in the Netherlands.
3. Improving the disposability of radioactive waste: optimising processes for efficient waste processing throughout the waste chain to be smart and suitable for geological disposal.

The programme is expected to contribute to:

- a strengthened national nuclear knowledge infrastructure and international network for geological disposal and radioactive waste.
- a societal discussion on geological disposal informed by up-to-date knowledge and based on taking societal responsibility for a final solution for radioactive waste.
- the consideration of the multinational repository option as a part of the dual-track strategy (I&W 2016).

1.5 Programme intervention logic

The intervention logic of a research programme describes how the programme's activities are intended to contribute to the goal and objectivess of the programme through foreseen outcomes and impacts. It gives insight in why certain activities are performed and what is needed to perform these activities. Furthermore, a clearly described intervention logic helps in the communication, monitoring and evaluation of a research programme. Figure 2 (see page 9) gives an overview of the programme's intervention logic.

The **inputs** to the long-term research programme are partly in-cash and in-kind (non-financial inputs). The in-cash inputs are the financial contributions from COVRA, added with co-funding from participation in external research programmes (e.g. EURAD). The in-kind inputs are the staff at COVRA, network of COVRA, research infrastructure (equipment, organisations, etc.) and research capacity (knowledge, skills, researchers and other external staff) that is allocated to and used in the programme.

The **activities** form the implementation of the programme and are described in Chapters 4 and 5. The type of activities within the programme are:

- Research into poorly indurated clays, rock salt, optimisation of disposability and waste processing and into the construction and engineering of a GDF. The research activities are organised in projects that are performed by research organisations as well as the researchers working at COVRA.
- Synthesis of the knowledge obtained from the research projects and development of safety cases and safety assessment for poorly indurated clays and rock salt.
- Collaboration and research into multinational disposal, to gather knowledge from and in collaboration with international partners of COVRA and to stay involved in discussions around multinational disposal.

- Communication and dissemination of the activities within the programme towards the general and interested public (including students).

The **outputs** are the direct results from the activities. Each output is directly linked to one or more specific activities, as indicated with the arrows in Figure 2. The activities are intended to lead to:

- Experimental data on host rocks and models preferably published in open access scientific publications and research reports, acceptance criteria and process guidelines as a result of collaboration and research.
- Reduced uncertainty in safety cases, safety assessments and cost estimation for final disposal. These outputs follow both indirectly from the research activities and directly from the synthesis and development of safety cases and assessments.
- Communication and intercation with public particpation in order to inform the public and stakeholders.

The **outcomes** are the effects of the activities and their outputs. These are more direct and short-term in comparison to impacts. The driving forces (see section 1.4) of the research programme are at the level of outcomes: these are marked with a blue border in Figure 2. In addition to these specific objectives the expected outcomes of the research programme are:

- Contribution to NPRA reporting cycle for the European Commission.
- Improved insights in the possibilities for a multinational disposal facility.
- Contribution to a well-informed societal discussion organised by the Rathenau Institute (Staten-Generaal 2019) and informed external parties and public (incl. students).

The **impacts** are the long-term effects (contributions in section 1.4) of the research programme. Impacts are often difficult to measure and only become evident over time. They are more indirectly related to the outcomes as a whole.

1.6 Responsibility and collaboration

The long-term research programme is a programme that is led and developed by COVRA in consultation with external experts and stakeholders. COVRA is responsible for the preparation of geological disposal in the Netherlands and has an operational need for technical and scientific information on the future geological disposal – as this affects current radioactive waste handling and packaging. Therefore, COVRA has taken the lead in developing, funding and managing the long-term research programme.

As the waste management organisation, COVRA is responsible for the identification of the research needs of the programme. The research needs are defined in cooperation with the programme's International Advisory Board, that also reviews and contributes to the safety case. The programme provides funding and co-funding for research projects that address the formulated needs. The programme is thus a collaboration between COVRA and selected research providers, preferably in the Netherlands.

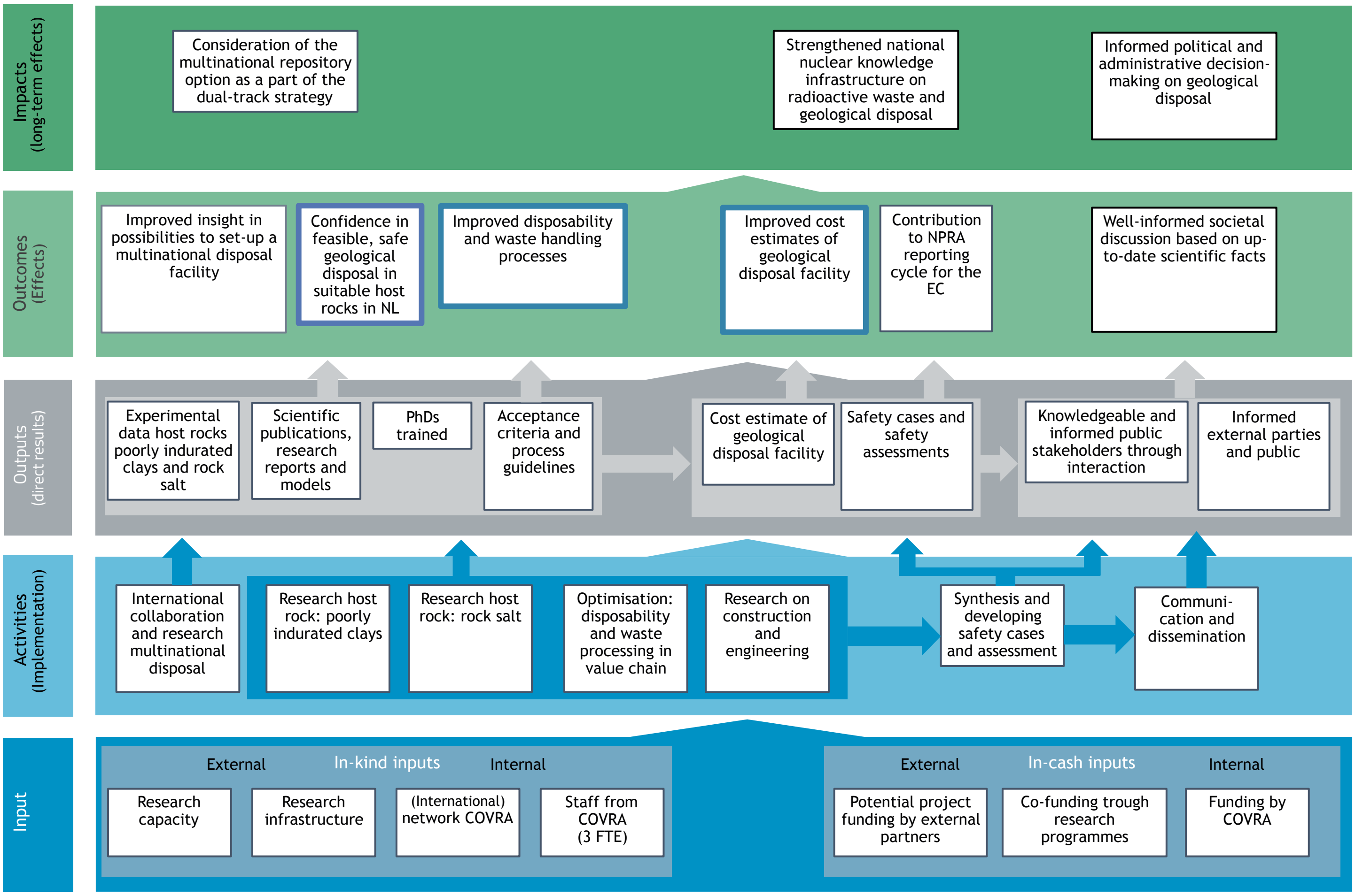


Figure 2: Intervention logic of the long-term research programme

The programme office, which is run by COVRA, monitors the quality of external research and adherence to the agreed terms of reference, but does not interfere with the research results.
In addition, the programme office also takes a lead in reporting (e.g. for the safety case and in international collaboration) based on the external research.

In the long-term research programme, informal interactions between the public participation programme on geological disposal are established (cf. section 6.3).
These interactions are intended to exchange information between both programmes. The idea is that both content and societal discussion go hand in hand: a societal discussion requires up to date knowledge on geological disposal, while the societal discussion may result in questions that require technical-scientific research.

The long-term research programme starts as an initiative of COVRA alone, but may be extended with additional public or private partners over the course of the programme. Such additional partners should contribute financially to the programme, but would not be directly involved in the research. They are offered co-decision making: once a partnership will arise, COVRA and the partner will form a steering committee that will overhead COVRA's programme director. Partners can contribute and co-decide on future programme periods as well.

Measurement equipment placed in rock salt. The measurement equipment was placed in the rock salt as part of a large-scale experiment within the Waste Isolation Plant (USA). Source Kristopher Kuhlman, Sandia.

How is the new research programme positioned?

2. Positioning of the programme

2.1 Previous programmes

COVRA's long-term research programme is not the first research programme for the geological disposal of radioactive waste in the Netherlands. In the last fifty years, there have been four stand-alone research programmes on the geological disposal of radioactive waste (see below).

The earlier research programmes have been led, funded and initiated by different organisations and were not long-term by design. This has led to several periods of inactivity between the earlier research programmes. The previous research programmes each had a different focus: the first three focused on rock salt as host rock formation, while OPERA focussed mainly on poorly indurated clay (specifically Boom clay) as host rock formation since much work has been done earlier in the Netherlands on disposal concepts for rock salt and, accordingly, only limited efforts within OPERA were performed to develop a Safety Case in rock salt.

Consequently, the major part of the OPERA research programme has been dedicated to the development of the OPERA Safety Case for Boom Clay (Verhoef and Schröder 2011, Verhoef et al. 2017). In this section, we provide a summary of the research programmes that took place during the past five decades (cf. Figure 3).

The first research programme was named after the Interdepartmental Commission on Nuclear Energy (ICK) and was set-up in the early nineteen seventies to find a more sustainable alternative for the handling of the Dutch radioactive waste. The ICK Commission found that rock salt formations might be a suitable option to serve as a host rock for geological disposal. The research and activities related to ICK lasted from 1972 till 1979. The research did not directly continue after the ICK Commission had published their results (Commissie OPberging te LAnd 1984).

In the years that followed (the early 1980s) radioactive waste remained nonetheless an important political point of discussion

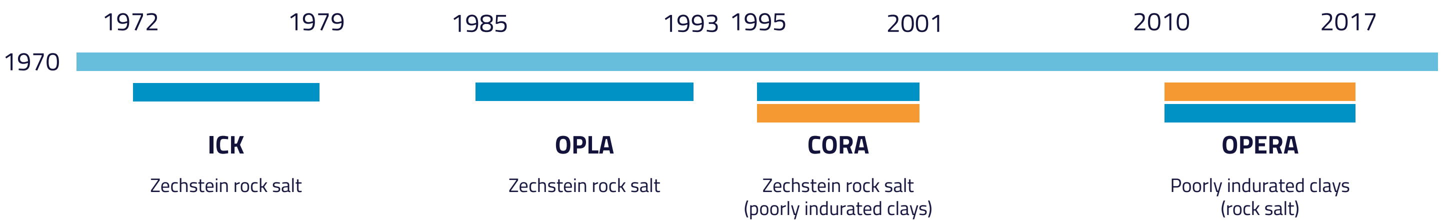


Figure 3: Overview of previous research programs.

and the Dutch government decided to set-up a national radioactive waste management organisation (COVRA). COVRA became the central organisation that manages and stores all Dutch Radioactive waste (COVRA N.V. 2019). COVRA had been appointed two tasks:

- The temporary safe storage of radioactive waste;
- Preparation and research for the final disposal of radioactive waste.

In 1984, shortly after the establishment of COVRA, it was decided that radioactive waste would be stored above ground for at least 100 years. The 100-year period was chosen to provide time to explore and develop the findings from the ICK research (Commissie OPberging te LAnd 1984) and with the intention to accumulate funding for the construction and operations of the GDF (Staten-Generaal 2019). This led in 1985 to the start of the OPLA programme. During the OPLA programme, the focus of the research on deep geological disposal remained on the use of rock salt as a host rock for the geological disposal facility. The programme lasted till 1993 (OPLA 1989). At the end of OPLA the conclusion was drawn that a repository in rock salt is a technical and safe solution for the final disposal of the Dutch radioactive waste (de Groot et al. 1993).

After OPLA was finished, a second gap in the continuity of research on geological disposal of radioactive waste in the Netherlands occurred. It took three years until the follow-up programme CORA started. The CORA programme was executed between 1996 and 2001. The CORA programme had a specific aim to research the retrievability of radioactive waste once it was placed in a deep geological disposal facility (CORA 2001).

When CORA was finished, the research stopped for a third and longer period: it lasted a decade until the research was reinitiated with the start of the OPERA programme in 2010. The long period of very limited research activities had as a consequence that earlier collected knowledge had to be recovered and that the research infrastructure on the geological disposal of radioactive waste had been diminished and weakened over time.

The OPERA programme lasted from 2010 till 2017. Its goal was to develop a national safety case and to explore opportunities to dispose radioactive waste in a specific type of poorly indurated clay, the Boom clay formation (Verhoef et al. 2017). OPERA involved researchers from a variety of Dutch and international research institutes and reengaged the scientific community to be actively involved in this research area (Verhoef et al. 2017). During OPERA, earlier retrieved knowledge was collected and analysed. The OPERA programme formed the fundament for the current long-term research programme.

Table 1: Overview of developments (Verhoef et al. 2017)

	OPLA (1982-1992)	**CORA (1995-2001)**	**OPERA (2011 -2017)**
Disposal concept	OPLA: objective was to study the possibility of radioactive waste disposal for three nuclear energy scenarios. ▪ Facility in domal salt or bedded salt ▪ Boreholes with a length of 2000-2500 metre in domal salt	CORA: disposal of reprocessed nuclear power waste products (CSD-v) was investigated. ▪ Facility in domal salt or bedded salt ▪ Disposal depth 800 metre ▪ Short disposal galleries to dispose 1 CSD-v (one vHLW canister	Generic, not site-specific, disposal facility in Boom Clay at a depth of 500 metres within a thickness of clay of 100 metres has been investigated. Minor efforts have been done for rock salt.
Experience elsewhere	In the Netherlands, there are open volumes generated in rock salt domes to explore salt by dissolution mining. The control of the open volume to be generated and stabilisation of the open volume is less with dissolution mining.	Tunnels in poorly indurated clay have been constructed, knowledge on this topic was therefore available.	The underground research laboratory (URL) HADES in Mol, Belgium 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 under-standing in the choices made between both programmes.

Construction	The description of the construction methodology is limited to 'conventional mining technique' 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	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 emplacement of waste packages is necessary.	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. In OPERA, radiological controlled zones do not exist as long as construction takes place. Co-activity risks are then excluded.
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 minimise 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.	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 resistance against the underground pressure and be corrosion resistant (Barnichon, et al. 2000).	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 super containers are loaded on a transport cart and transported with a battery-driven locomotive to the disposal gallery.
Closure	In OPLA, the brine is suggested to be removed from the borehole and closure was envisaged by creep of the salt.	In CORA, clay-based materials, sand or gravel were chosen to be used as backfill. Cement-based materials were not advised to limit the alkaline plume.	OPERA, the backfilling of the transport galleries is suggested to be foamed concrete to provide additional mechanical support. The potential alkaline disturbed zone is not calculated but foamed concrete is not expected to be the main contributor since it is easily carbonated due to its high gas permeability. The shafts can be backfilled with excavated material such as sand and bentonite. A part of the lining of the shafts may need to be removed to minimise interfaces along which radionuclides can potentially easily migrate.
Response parliament	The Dutch government introduced the concept of retrievability of the waste to have human control over the closure of the facility and emplacement of waste packages.	After CORA was finished, the parliament was convinced that the retrievability of waste was technically possible with the proposed disposal concept.	
Assumptions safety assessment		In both research programmes, calculations have been performed in order to assess the post-closure safety of disposed waste.	

2.2 National policy

The national policy making on radioactive waste is the responsibility of the Ministry of Infrastructure and Water management. Authority for Nuclear Safety and Radiation Protection (ANVS)[1] has the duty to regulate and monitor the nuclear activities in the Netherlands. All EU member states have the duty to regulate and monitor the nuclear sector within their country, including radioactive waste management and geological disposal. To perform this task, the Ministry has set-up in 2016 a national policy programme on radioactive waste (NPRA) that is in line with the 2011/70/Euratom guidelines (I&W 2016).

COVRA's research programme is carried out within the framework of the national programme on radioactive waste. The NPRA covers two topics (1) policy and (2) process and implementation that are also relevant to the geological disposal of radioactive waste.

NPRA policy

The NPRA (I&W 2016) has been designed in such way that the handling of radioactive waste is managed safely and responsibly manner. To ensure that the waste is handled with care, the NPRA includes different requirements that guide research on disposal. The three most important requirements are:

1. **The waste creation should be minimised.**
   Radioactive materials can only be used if there are important economic or social benefits gained by the activity. If the organisation fulfils the requirements that are needed to create radioactive waste, it has to make sure that the waste is reduced as much as possible in volume and activity.
   The Dutch policy on minimisation is open for decay storage in order to re-use valuable (raw) materials when their activity has decayed to permissible levels.
2. **The management of the waste should be safe for current and future generations.** The Dutch radioactive waste will be stored in the waste management facilities at COVRA for the next 100 years until the geological repository is realised. The rationale behind this approach is that it takes a century to gather enough waste and financial means to build a geological disposal facility. In addition, there are further benefits to maintain the 100 years period:
   a. A part of the radioactive waste will decay into a stable element and can therefore be processed as regular waste.
   b. During the time that the waste is kept above ground, high-level radioactive waste can release heat. When cooled down the waste is easier to handle for geological disposal.
   c. The long initiation period gives constructors and society the time to find a suitable location through a structured public participation and site selection process.
   d. The realisation of geological disposal facilities in other countries will lead to more knowledge of the construction and operation of geological disposal facilities.
   e. Possibilities may arise to build a shared multinational geological disposal facility. The Netherlands adheres to a dual track policy: both a national as well as a shared multinational geological disposal facility are official policy options.
   f. New technologies, such as transmutation or partition, could potentially decrease the volume of high-level waste in the future. This would then reduce the volume of radioactive waste to be disposed.
   The NPRA states that if the circumstances considering radioactive waste changes in the future the 100 years initiation period might be altered.
3. **To guarantee that the waste is retrievable (I&W 2016),** The Dutch government decided that all decisions made on the geological disposal of radioactive waste should be

1. The ANVS is an independent administrative authority and is answerable to the Minister of Infrastructure and Water management.

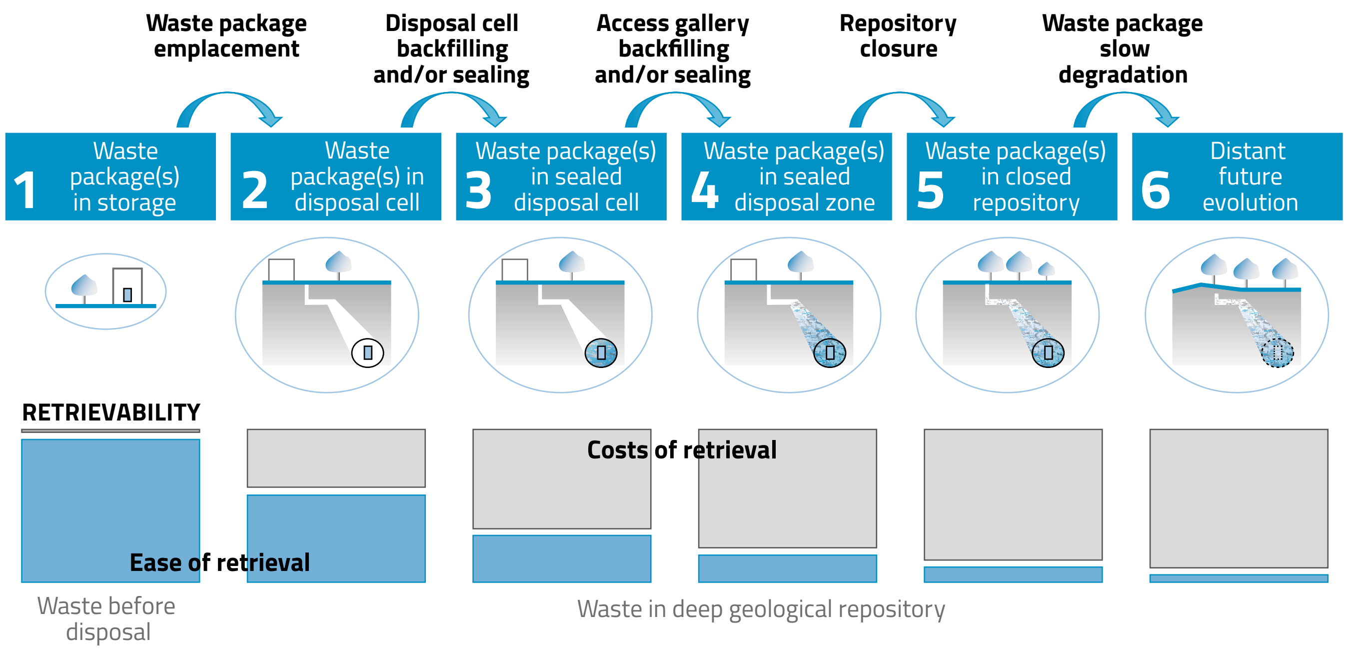


Figure 4: Stages of a geological disposal facility and associated changing degree of retrievability and costs of retrieving waste (source: COVRA, based on OECD NEA)

reversible. The demand for retrievability has been included in the Dutch policy regarding radioactive waste since the 1980 (VROM 1993). Retrievability is set as a norm to ensure that it remains possible to re-use waste (when new techniques make it possible to use it for new applications), to retrieve the waste and adapt the facility when necessary. The ease of retrievability and the costs associated with retrieving waste changes over time, which is visualised in Figure 4 (I&W 2016).

NPRA implementation

The part of the NPRA that describes the process and implementation outlines a mission towards the realisation process of the geological disposal facility. The mission has two aspects:

1. **Delayed decision making ("not now").** The NPRA underlines that the future is too uncertain to make far-reaching decisions during the upcoming 70 years. Therefore, the NPRA suggests that a flexible approach based on up to date knowledge will contribute to the eventual best permanent handling of the waste.
2. **Open and inclusive decision making.** The European Directive 2011/07 / Euratom stipulates that, in accordance with national legislation and international obligations, the public must have the opportunity to participate effectively in the decision-making process on this matter. The purpose of participation in the decision making on disposal is that around the year 2100 or as much earlier as necessary, a broadly supported choice will be made in the Netherlands on the future method of managing radioactive waste.

The long-term research programme of COVRA contributes to the implementation of the NPRA. It will be important in generating and integrating knowledge that is needed to make evidence-based decisions on the final disposal of radioactive waste. The programme will be instrumental in acquiring knowledge and strengthening the national knowledge infrastructure by setting-out research questions and funding researchers in the Netherlands. As such, it contributes to the technical/scientific side of the open and inclusive decision making. In addition, the research programme will foster interaction and contribution to the societal participation process that is organised by the Rathenau Institute. The programme will feed societal discussions with the most recent facts and figures and intends to have a positive impact on the general public knowledge on this matter. As such, it also contributes to the societal side of the decision making.

2.3. Current national landscape

The nuclear sector in the Netherlands is quite broad: the nuclear supply chain is quite well covered in the Netherlands, although with limited redundancy (Technopolis Group 2016). For almost each stage in the nuclear supply chain only one organisation is active in the Netherlands. Virtually all these organisations produce radioactive waste and are clients of COVRA as the designated waste management organisation (WMO). As such they are stakeholders of the research programme for geological disposal, specifically as research may change waste acceptance criteria and/or influence waste fees. Other stakeholders do not provide radioactive waste, but act as regulator, research partner or environmental organisation.

Knowledge and research stakeholders

The ANVS is formally assisted by the RIVM as its Technology Support Organisation (TSO) on questions related to radioactivity, including geological disposal. Regarding geological disposal, the RIVM is especially knowledgeable in questions related to radionuclides in the biosphere. The RIVM has good research capabilities and a wish to deepen their expertise on geological disposal. Therefore, RIVM is one of the knowledge partners in the long-term research programme.

The long-term research programme heavily relies on external research partners to provide answers to COVRA's research

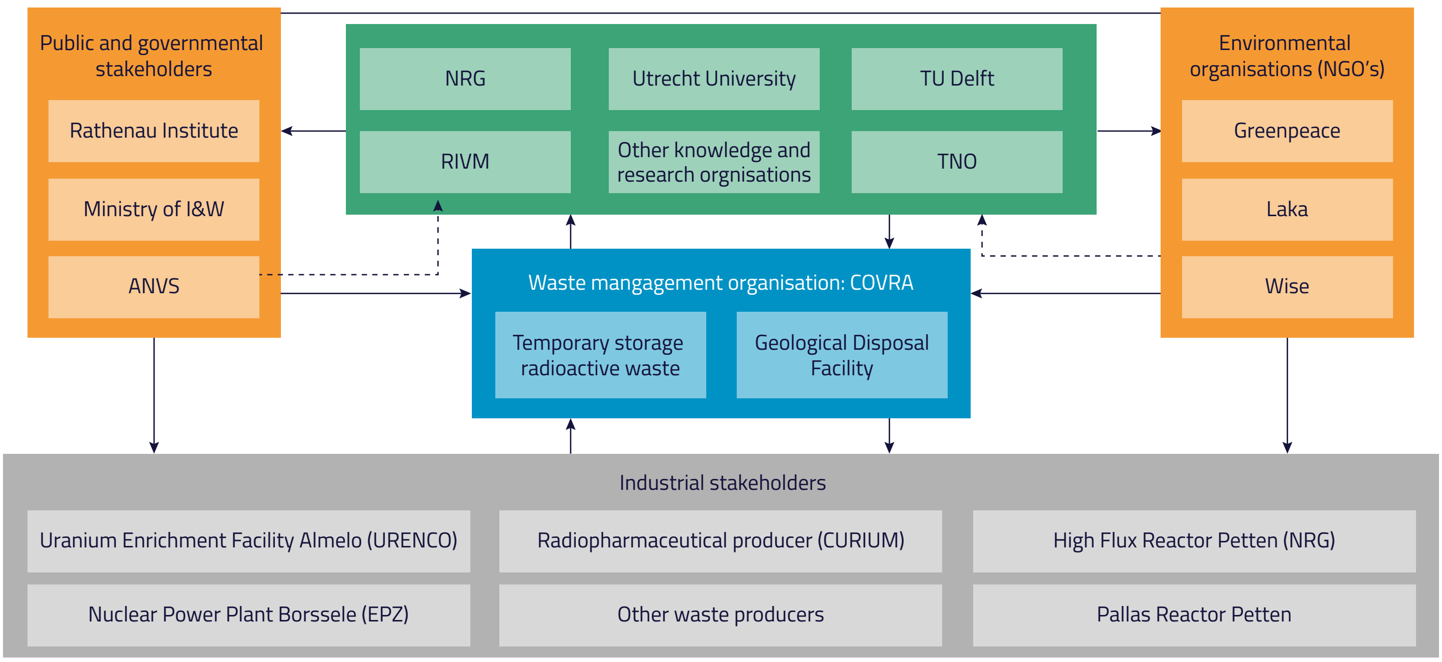


Figure 5: Overview of the current national landscape (anno 2020)

questions. In the Dutch nuclear sector several academic and other research and technology organisations (RTOs) are active that are of interest to the geological disposal of radioactive waste. NRG and RIVM are among these RTOs. NRG has been strongly involved in previous research programmes on geological disposal of radioactive waste, while RIVM (as TSO) is building up capacity on this specific topic. TNO is another RTO. As the geological survey of the Netherlands, TNO is very experienced in researching the Dutch geology and has a lot of data and bore hole samples of the Dutch subsoil, including rock salt and poorly indurated clays. TNO has extensively participated in previous programmes on geological disposal of radioactive waste as well; they have coordinated OPLA and CORA.

The academic research on radioactive waste and geological disposal is done mainly at the Delft University of Technology (TU Delft) and Utrecht University (UU). The TU Delft hosts the Reactor Institute Delft (RID) where since the early 1960s fundamental research has been performed on energy, materials and health applications. The RID in collaboration with the Department of Radiation, Science & Technology forms the Dutch knowledge centre for radiation-related research. Also, on Geo-Engineering the TU Delft has several relevant research activities, for instance in the framework of DAPWELL – in which relevant geological formations (potential host rocks) are studied for harvesting geothermal energy. Similarly, the Department of Earth Sciences of the Utrecht University has strong research capabilities on geology, geomechanics, geochemistry and experience with radionuclide migration in the subsoil. Both universities have been involved in previous research programmes on geological disposal of radioactive waste. The TU Delft is currently also involved in one of the European EURAD projects with co-funding from COVRA.

2.4 International context

COVRA participates on a European and a global level in international collaboration groups. International collaboration can serve several purposes: R&D, better regulation, process development, skill development and mutual understanding. This variety of purposes leads in all cases to one shared goal: knowledge on how to construct and manage radioactive waste disposals. From 2020 onwards it is especially of high importance to stay involved in these international collaborations since countries are starting the preparation and construction of their geological disposal facilities. During the licensing process and construction phase, valuable lessons can be learned and experiences can be gained.

The long-term research programme has to integrate the knowledge that has been/will be developed beyond national borders. In order to be able to gather this knowledge, COVRA has to bring knowledge as well to stimulate the exchange of ideas, insights and methods. To do so, COVRA participates on a European and global scale in international working groups: OECD NEA, IAEA, ERDO and EURAD all contribute to better understanding waste management and the construction of geological disposal facilities.

On a global scale there are two organisations that play a particularly active role in knowledge sharing: the International Atomic Energy Agency (IAEA) and the Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD NEA). OECD NEA is an organisation focused on developing nuclear co-operation between participating countries and launching R&D undertakings. During the past three decades, as a part of these activities, OECD NEA hosts the Clay Club, the Salt Club and the Crystalline club (OECD NEA 2019). These clubs are established as international working groups to examine host rocks for geological disposal facilities. The three clubs aim to share experience and built on each other's understanding of the topic to develop the knowledge areas.

The second organisation with a worldwide reach that is relevant for COVRA is the IAEA. The organisation aims to facilitate access to nuclear power and other nuclear technologies and strengthening promotion/development of nuclear science, technology and applications. To achieve these aims, the agency takes action to improve nuclear safety and security, provide effective technical cooperation and deliver effective and efficient Agency safeguards (IAEA 2019). One of these activities is the publication of good practices for "meeting and demonstrating compliance with, the safety requirements on Disposal of Radioactive Waste in a systematic and comprehensive manner" (IAEA 2019).

On a European level COVRA collaborates within the European Repository Development Organisation (ERDO) working group and participates in the EURAD programme. The ERDO-wg has been set up to support countries with a smaller nuclear power programme and countries with no nuclear power but with radioactive wastes to explore the opportunities to potentially built a shared geological disposal facility. The ERDO working group ensures that there is a continuous collaboration between countries for which the building of a national repository is a challenge. ERDO-wg is combining resources to demonstrate the feasibility of enhancing safety and security of a shared geological disposal facility. The participating parties recognise the potential that a shared facility has, but still develop their own national research programmes. This approach of participating both on a national and international level is called the dual track approach. ERDO-wg has benefits that count on an international and national level. The international benefits are increased visibility for participating countries, investments savings by preventing repetitive research, increased influence for smaller nuclear countries in international bodies and increased influence on suppliers of nuclear technology and fuels. The benefits on a national level are a credible approach on the management of national radioactive waste, reduced R&D costs, increased pooled research and wider accessibility to skills and technologies (ERDO 2019).

Besides the ERDO-wg collaboration COVRA also takes part in the EURAD programme. EURAD is a European Joint Research programme on further developing the safe management and disposal of radioactive waste. EURAD aims to bring together a broad range of technical and scientific parties that are willing to contribute to the improvement of waste management solution across Europe. The research and knowledge that is developed through EURAD has beforehand been defined in a roadmap with a project-oriented approach. This roadmap consists of work packages with specific projects in which involved parties can participate. EURAD has been designed in such a way that it ensures that the interests of small, large, advanced and less-advanced countries are included in the research questions. The main challenges that are identified by EURAD are: to increase knowledge for the safe start of operation of the world's first geological disposal facilities for high-level and long-lived radioactive waste / spent nuclear fuel in the advanced Member states within the next decade, to improve innovate and develop science and technology for the management and disposal of other radioactive waste categories and to manage and transfer knowledge and competences between generations and across Member States national programmes (EURAD 2019).

Bird eye view on the only nuclear power plant in the Netherlands. This nuclear power plant is located in Borssele, Zeeland. Source: COVRA.

How can the current activities contribute to an efficient disposal of waste?

3. Organisation, structure and timeline

The overall organisation and structure of the long-term research programme is developed for the full timeline of the research programme. Of course, after each programming period this structure can be revised if needed. In this Chapter, we present the governance structure, the roles and functioning of the programme management and the International Advisory Board. Furthermore, we provide a structure for the long-term research programme and the overall timeline. At the end of this Chapter, the work package dealing with programme management is described in more detail.

3.1 Governance structure

The governance structure has been set-up to ensure that the research programme functions in a logical and sensible way. The governance structure contains two types of entities: the COVRA programme management and the external partners.

The programme management includes a programme director and a programme office. For both parties there are general tasks that have to be executed while the programme is active. These tasks are reporting, coordination of the programme, providing continuity, driving an exchange of knowledge and insights, and collecting knowledge & information through participation in the international bodies/forums in which COVRA takes part.

In addition, the programme director manages the international advisory board (IAB) and approves the safety cases. The programme office produces the safety cases while at the same time it sets out questions that can lead to the acquiring of knowledge and information from the funded research, education and technology organisations. It further provides funding, knowledge and information to the international bodies and forums (the role of the programme office will be set-out in more detail in the next paragraph).

The four types of external partners are positioned on the borders of the governance structure in figure 6. The external partners have all separate tasks that should directly benefit the quality and the impact of the programme.

The international advisory board consists of four members that are all international experts on radioactive waste. The international advisory board will provide the internal parties advice on the process of the programme and will use their experience to assist where necessary.

The research, education and technology organisations (research partners) are in a project-based relationship connected to the programme. The research partners are given opportunities to do specific projects that are needed to gather new or more in-depth knowledge that can feed into the knowledge base and/or the safety case management by the programme office.

The international bodies in which COVRA participates are the third type of external partners. The international bodies have a passive role since they cannot actively provide any input to the programme. The programme director or the programme office actively participates in international meetings to gain new insights or knowledge.

The fourth external partner that is (informally) included, is the societal participation trajectory of Rathenau Institute.
The Rathenau Institute has been tasked by the Ministry of Infrastructure and Water Management to set-up a societal participation trajectory on geological disposal of radioactive waste. The long-term research programme intends to inform this trajectory with facts and figures that results from the programme's research activities.

3.2 Programme management

The programme management is set up to ensure that the research programme is directed in an effective and efficient manner and results in the desired outputs and outcomes. The programme management owns the safety cases for poorly indurated clays and rock salt and integrates the results of the programme's activities (tasks) into the safety cases. The programme management is responsible for the procurement or tendering of external research projects, which they guide or monitor to gain the knowledge and information needed to produce the safety cases. In addition, the programme officers (POs) are involved in international networks and coordinate and participate in internal and international research activities.

The programme management is tasked with (not exclusively)[2]:

- Managing the research programme
- Interacting with the IAB;
- Publishing calls for external research projects and selecting proposals;
- Allocating funding to external activities/projects;
- Monitoring progress and quality of external projects and managing internal projects;
- Acquiring and analysing knowledge and data for the safety cases and disposability;
- Integrating acquired information and producing Safety cases;
- Maintaining interaction with (industrial) stakeholders, involved external researchers and the relevant Dutch and international research community;
- Representing the research programme in national and international forums and meetings, and following international research;
- Initiating or organising communication or dissemination activities of findings to internal and external partners;
- Contributing to education and dissemination of up-to-date knowledge to students and society.

The programme management is run by a programme director and several programme officers. The programme officers currently have each a specific area of expertise: geological disposal in Dutch rock salt, geological disposal in Dutch poorly indurated clays, and multinational disposal and overarching issues. The programme management is seated at COVRA in Nieuwdorp (Zeeland).

3.3 International Advisory Board

The programme director and programme office are advised by an International Advisory Board (IAB) consisting of international experts in fields crucial for the geological disposal of radioactive waste. The goal of the IAB is to assure the quality of the research programme and its outputs, assure its international embedment and its linking with adjacent initiatives in the Netherlands and abroad, and to strengthen the research programme based on input from international experts. The IAB may meet in different compositions depending on the needs for advice by the programme director and programme office. The activities of the IAB are primarily of advisory nature, but some experts in the IAB will also contribute to the documentation of the preliminary safety cases developed in the research programme. In this section we describe in detail the role, function and constitution of the IAB.

The IAB will be installed on the recommendation of the programme director. The IAB will constitute of four members with complementary and partly overlapping expertise. The members will be installed for the first five years of the research programme, which may be extended with another five years in mutual agreement at the end of the programming period. The expertise and role of the selected international members of the IAB are described in Table 2.

2. This list of tasks is not limited and may be extended during the execution of the long-term research programme.

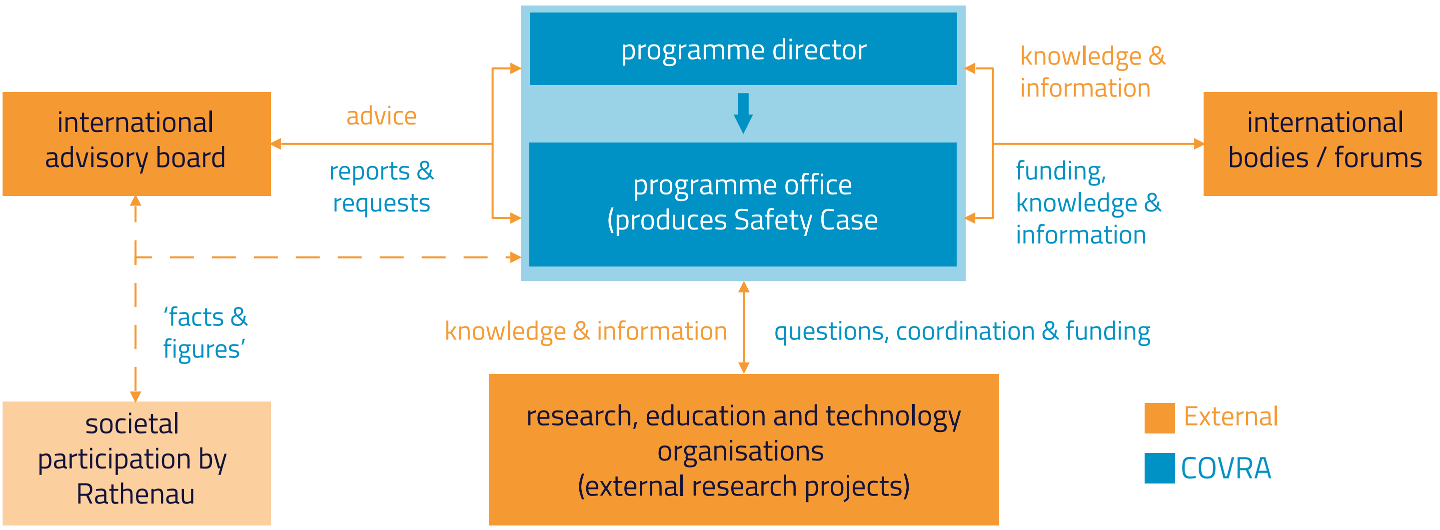


Figure 6: Organogram for COVRA's Long-term research programme

Expert	Expertise	Role
Dr. Charles McCombie Arius Switzerland	Expert on geological disposal of radioactive waste and radioactive waste management	Advise and review in relation to safety case, international developments/collaboration, multinational disposal, disposal concepts, disposability and costs, and contribution to safety case writing
Prof. dr. Neil Chapman University of Sheffield The United Kingdom	Expert on geological disposal of radioactive waste and radioactive waste management	Advise and review in relation to safety case, international developments/collaboration, multinational disposal, disposal concepts, disposability and costs, and contribution to safety case writing
Dr. Maarten Van Geet ONDRAF-NIRAS Belgium	Expert on geological disposal of radioactive waste in poorly indurated clays	Advise and review in relation to geological disposal of radioactive waste in poorly indurated clays Linking pin between the Belgium research activities and the research programme
Dr. Nina Müller-Hoeppe BGE Technology GmbH Germany	Expert on geological disposal of radioactive waste in rock salt	Advise and review in relation to geological disposal of radioactive waste in rock salt Linking pin between the German research programme and activities

Table 2 : Experts and roles in the International Advisory Board.

The IAB is an advisory board alongside the programme director and programme office. The programme director acts as the secretary of the IAB and will act as the contact point to the IAB. He will also request meetings with the IAB, which may be held in full or partial composition depending on the topics to be discussed. The meetings will be attended virtually and on-location (face-to-face) on request. The IAB will be financially, administratively and organisationally supported by COVRA.

The IAB and its individual experts may be consulted by the project director and the programme office for any of the following activities:

1. Advise on the set-up of the research programme and the five-year work programmes, including the societal interactions therein;
2. Advise on the direction and continuation of the research programme and strategic considerations that may arise during the execution of the programme;
3. Advise on the research topics and questions addressed in the five-year work programmes and the prioritisation thereof;
4. Advise on the international development and embedment of the research programme to ensure international knowledge transfer, participation in international research programmes and synergy between activities abroad;
5. Advise on the selection and quality assessment of external research projects, including potential research partners to invite for participation;
6. Advise on the quality assessment of research outputs, their validity and use in the safety assessment, cost calculation and safety case;
7. Advise on current societal questions and needs and ways of communication towards stakeholders (including industry, government and NGOs) and the general public;
8. Reviewing of the integration and synthesis of research outputs, cost assessments, safety assessments and the overall safety case;
9. Contributing to the writing of the safety case.

The IAB will meet at least once per year but may meet more often on request.

3.4 Structure of the long-term research programme

The long-term research programme has a structure that can be used during several programming periods. The structure follows the components of the geological disposal system and is described in terms of work packages (WPs). Each work package contains a set of tasks that are related in function or topic. The work packages are functionally related to each other, as visualised in Figure 7.

Work package 0 **(WP 0)** is overarching in the research programme and concerns all tasks related to programme management and coordination. The tasks in this work package are performed by the programme office at COVRA and are more or less similar during all programming periods. A detailed description of the tasks in this work package can be found at the end of **this Chapter**.

The work packages 1 and 2 **(WPs 1-2)** have a more strategic and integrative character. WP1 is related to strategic aspects in the research programme, such as costing and shared solutions and other strategic studies. WP2 covers the integration of the knowledge obtained through the research programme and the production of both safety cases. The tasks (projects) in these work packages differ per programming period. For the programming period 2020-2025 the tasks in these work packages are described in **Chapter 4**.

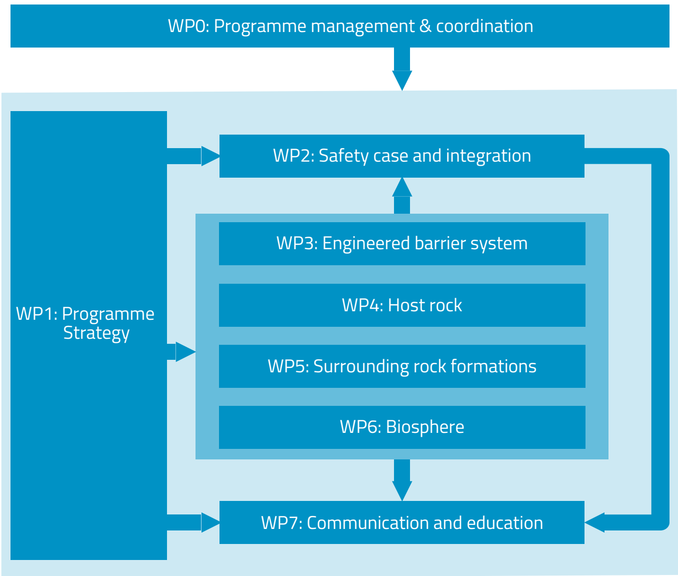


Figure 7: Overview and relation between the programme's work packages

Four work packages **(WPs 3-6)** are structured around key topics that need to be studied in order to produce safety cases; these are related to the components of the geological disposal system (cf. Figure 13). These work packages contain the main research activities of the research programme. The tasks that these work packages cover in the programming period 2020-2025 are described in **Chapter 5**.

The last work package **(WP 7)** covers all interactions of the research programme with society The tasks in this work package are described in **Chapter 6** including education, communication and interaction with public participation in the long-term research programme.

3.5 Overall timeline

The long-term research programme will cover a period of at least 30 years. In this period there will be several major events that will influence the national nuclear landscape of the Netherlands. During the first five years, the High Flux Reactor in Petten is planned to be taken out of operation and the construction of Pallas will start. A few years later the only Dutch nuclear power plant (KCB) is planned to be closed as well. Only Pallas has a horizon beyond 2050, meaning that up to 2050 there is still quite some activity and applied knowledge about radioactive waste (and the production thereof) in the Netherlands.

During the same time, internationally interesting developments will occur. Finland is starting to operate its geological disposal facility and Sweden will start the construction of its geological disposal facility. France will make major steps towards construction as well and some countries will move into site selection. These experiences in site selection, construction and site operation abroad will provide valuable information and lessons for the Dutch research programme.

To be able to adjust to this changing international and national landscape the programme will make use of a rolling agenda that is updated every five years. The rolling agenda sets 10 year and long-term goals for the programme, while developing a specific agenda to work towards these long-term goals for every five years. This practice makes the programme flexible and adaptable to changes within policy, society and science and technology.

The five-year rolling agenda will be aligned with the review cycles of the national programme on radioactive waste (NPRA) by the Ministry of Infrastructure and Water Management. The NPRA is produced in the framework of the European Directive for the responsible and safe management of radioactive waste (EU 2011). The NPRA is reviewed and updated every 10 years, i.e. in 2025, 2035, 2045. The long-term research programme ensures that the safety cases are scheduled to be ready before the Ministry reports its updated NPRA to the European Commission.

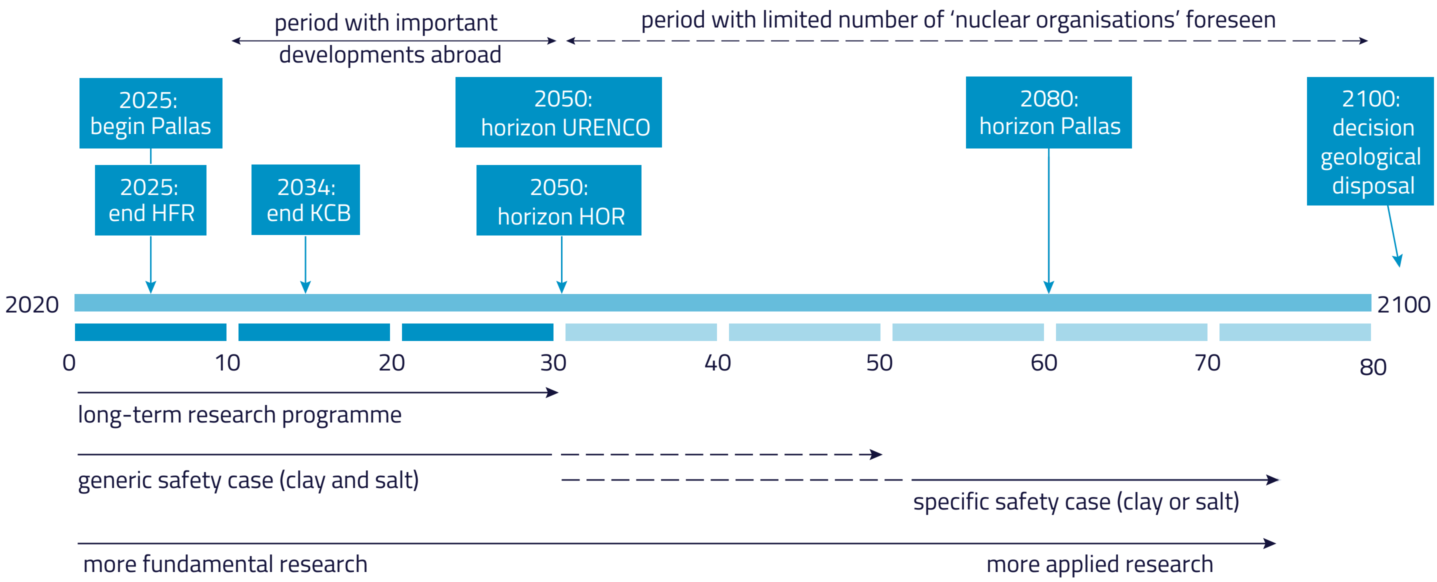


Figure 8: Timeline for geological disposal of radioactive waste in the Netherlands

The rolling agenda is implemented in the form of five-year work programmes. The first five-year period will start in 2020 and will finish in 2025. The detailed content of the first work programme are provided in Chapters 4 and 5, while in section 7.4 more information is given on the planning of the first work programme.

Production of generic safety cases

During the thirty years of the long-term research programme, no siting for a GDF is foreseen in the Netherlands. During this period, every ten years generic (non-site specific) safety cases will be produced (cf. Figure 8). Every five years an update of the cost estimate and a summary report of the most important findings will be published. These safety cases contain (1) a preliminary safety assessments of the Dutch radioactive waste disposed in a GDF in rock salt or poorly indurated clay and (2) a completed safety strategy, as developed in the OPERA safety case (Verhoef et al. 2017).

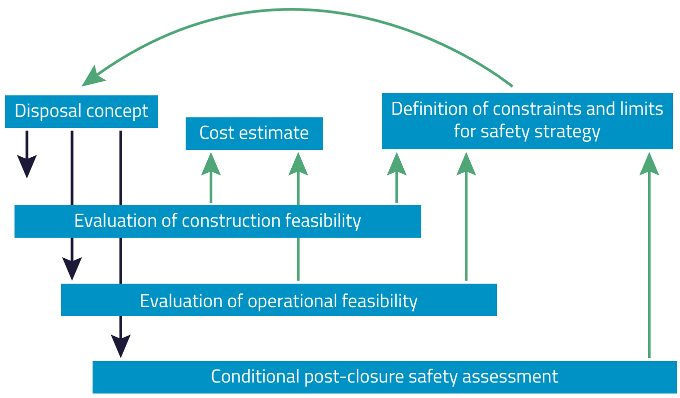


Figure 9: Cycle for updating the disposal concept and costs

The chemical and physical uncertainties associated with the disposal of all Dutch radioactive waste stored at COVRA's premises can be further identified in generic or non-site-specific safety cases. The implementation of the proposed and developed approaches will provide sufficient characterisation of the radioactive waste for disposal. The disposal concept and the costs associated with this concept will be continuously updated by new requirements in civil engineering and radiation protection. Figure 9 shows the cycle that will be run for the next decades, the post-closure safety assessments will remain conditional until a site has been selected.

3.6 Prioritisation

From an international perspective, COVRA's long-term research programme is modest in scale and scope. This reflects the long-term policy context and the size of the nuclear sector in the Netherlands. Therefore, the programme is designed to efficiently acquire knowledge through international collaboration and through selective research activities within the Netherlands.

The size of the programme's budget, the timeframe of the work programme and the capacity at the programme office (currently 3FTE) requires priority setting of the research activities. COVRA has therefore developed a framework to assess and assign priorities to each task in a work programme. For tasks related to the geological disposal system, this prioritisation is based on the three drivers for research for the geological disposal system (cf. Foreword). In addition, we also discern Unique Opportunities (UOs). These are unique opportunities to participate in co-funded (international) research activities that allow for efficient knowledge gathering, even though their urgency may be lower. In those cases, participation is considered (long-term) strategic and is therefore important to fund.

The table 3 below provides an overview of the prioritisation of research activities (tasks) in the programme.

The prioritisation of each task is given in the titles of each task in the work programme. In case of a unique opportunity, no priority is shown, only unique opportunity. A short explanation for the assigned priority or UO is given in each task description.
All projects with a Priority of 1, 2 or UO are (co-)funded during a work programme (upfront budget reservations). If additional funds become available during the period of the work programme, tasks with a lower priority will be considered for (co-)funding. In the budget some funding is reserved to participate in unforeseen unique opportunities arising during the work programme.

More details on the prioritisation of tasks related to the geological disposal system are provided in the remainder of this section.

Prioritisation of tasks related to the geological disposal system

The prioritisation of tasks related to the geological disposal system follows the three drivers for research (cf. Foreword). These drivers have been applied in the OPERA safety case to construct priorities for the components of the disposal system:

- Confidence in long-term safety (S): the extent to which a task contributes or is important to the long-term safety of

Table 3: Overview of priorisation of research activities in the porgramme.

Type of prioritisation	Scale	How assessed and assigned
Priority based on three drivers for research for the geological disposal system (for components of the geological disposal system, tasks follow priority of components)	Numerical: 1-4 1 = highest priority 4 = lowest priority	1 = large score on two or more of the drivers 2 = large score on only one of the drivers 3 = medium score on one or more of the drivers and a low score on the other drivers 4 = small score on all of the drivers
Unique Opportunity (UO)	Binary: UO or not	UO = unique opportunity to strategically participate in a co-funded (international) research activity or to meet a policy need

disposal. Measured along a three-level scale: small, medium, large.

- Disposability (D): the extent to which a task contributes or is important to the disposability of radioactive waste. Measured along a three-level scale: small, medium, large.
- Costing (C): the extent to which a task contributes or is important to better understand and optimise costs for a GDF. Measured along a three-level scale: small, medium, large.

The resulting priorities of the components of the disposal system is shown in Figure 10. The host rock receives the highest priority as two of the three drivers have a high score, while the biosphere receives the lowest priority as all three drivers have a low score. Both for poorly indurated clays and rock salt as host rock, this framework results in the same component prioritisation.

The prioritisation of tasks (and thus research activities) within the research programme is based on the prioritisation of the components of the geological disposal system. Tasks receive the same priority as the component to which it is related (work package) or, in specific cases, a lower priority. The argumentation for a lower priority is provided within the task's description.

The scores for each of the drivers, and thus the priority, may change over time. The scores are conditional: once certain knowledge or information is obtained, other research activities may become more important to get improved confidence in long-term safety, disposability or costing. Tasks are thus in-part conditional and therefore also ordered over time through this prioritisation. During the development of each work programme the priorities, and the assessment of drivers on which the prioritisation is based, are revisited and changed if needed.

Unique opportunities

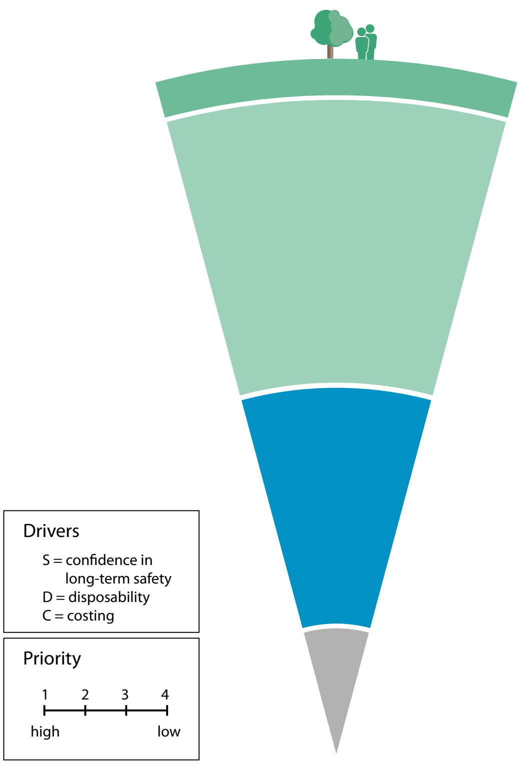
Not all tasks can be prioritized based on the drivers, but depend on unique opportunities to collaborate or support strategic policy needs. Unique opportunities can be a strategic participation in a co-funded (international) research activity or international collaboration. Unique opportunities can also be related to tasks needed to meet policy needs or requests. For instance, tasks related to multinational disposal solutions are needed to fulfil the Dutch dual track policy or questions from the societal participation trajectory of Rathenau Institute.

The prioritisation of these opportunities may change over time as well, as their importance may change. The prioritisation is conditional: policy needs may evolve and certain needs are more or less important in some stages towards the preparation of geological disposal of radioactive waste. During the development of each work programme, priorities are revisited and changed if needed.

3.7 Procurement and tendering

COVRA's long-term research programme is funded by COVRA. COVRA will directly invite one or more external service providers to put forward a proposal. In specific cases, the programme director can decide to publicly tender its request for technical and scientific research.

Within the research programme, procurement will follow the process of tendering: COVRA will request a (research) proposal based on a Terms of Reference (ToR). For each procurement COVRA



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

Figure 10: Prioritisation of components of the geological disposal system based on drivers for research (Verhoef et al. 2017)

will develop a specific ToR in which the objectives of the request for services; the research question(s) and/or the foreseen tasks and deliverables; the timeline for the services and the deadline and conditions for the requested (research) proposal are described. In addition, the proposal selection process and criteria will be described. An indication of the maximum budget may be given.

The tenderer who meets all criteria and passes the selection process as most successful will be awarded the contract. If needed, a negotiation phase may result in a request to adapt the (research) proposal before the contract is awarded. The proposal will be used by the programme office to manage the contract and monitor the progress of the awarded research project.

3.8 Work package 0: Programme management and coordination

This work package covers all management and coordination tasks of the programme office, including international collaboration. Many of these tasks have in more general terms been introduced in this chapter. Here we shortly describe each task in more detail.

Task 0.1: Programme management and monitoring

The management of the research programme is done by the programme office, following the governance structure and responsibilities outlined in sections 3.1 and 3.2. The goal of this task is to ensure that the research programme fulfils its goals according to the five-year work programmes and within the available budget. To that end, the programme director manages the research programme with the help of the programme officers. Together they monitor the progress of the research activities against the specified timeline, budget and Terms of Reference (if applicable).

Task 0.2: International collaboration and networking

Part of the research programme is to follow and participate in international collaboration and networking to share information and work together in topics beneficial to several participants. This is done through different organisations and platforms which were introduced in section 2.4. Here, a more detailed description of organisations or groups in which COVRA participates are given. Specific description of international projects that are performed within these organisations and groups are included in Chapters 4 and 5.

The ERDO working group, which was shortly introduced in section 2.4, ensures that there is a continuous collaboration between countries interested in a shared repository option. ERDO projects are described in WP1. During this research programme more collaboration might arise, which will be handled as part of the programme.

NEA Clay Club examines argillaceous rocks considered for geological disposal of radioactive wastes. These rocks range from soft clays to indurated shales and display properties which are favourable for repository host rock or -barrier materials.
Clay Club coordinates the research, and shares the findings of studies (e.g. mineralogy geochemistry, porosity, pore geometry, hydraulic properties etc.) and complementary numerical modelling, with each other and with wider audiences.

NEA Salt Club develops and exchanges scientific information on rock salt as a host rock for geological disposal of radioactive wastes. With this information and knowledge exchange the Salt Club also wants to raise the interest in new countries to consider rock salt as a repository host rock. As well as working with the technical aspects, the working group also aims at sharing the information with other programmes and interested parties and at training of future experts on rock salt.

NEA Thermodynamic Database Project (TDB) aims to provide a comprehensive, internally consistent, quality assured and internationally recognised chemical thermodynamic database to meet the specialised requirements of safety assessment modelling of radioactive waste disposal systems.

NEA Integration Group for the Safety Case (IGSC) aims to assist member countries to develop safety cases. The nature of safety cases means that input from different disciplines is needed and IGSC provides a platform for experts to communicate.

Natural analogies working group (NAWG) explores the developments in the use of natural analogues in supporting safety cases for the disposal of radioactive waste.

IAEA International Project on Demonstrating the Safety of Geological Disposal (GEOSAF III) was originally launched to harmonise the demonstration of safety of geological disposal facilities during and after their operation. Integrated safety assessment that covers both operational and post-closure period, is required for licencing a geological disposal facility for radioactive waste. GEOSAF has previously developed and reviewed a safety case for a GDF and developed an approach for operational safety for geological disposal and its impact on long-term safety.
Now GEOSAF focuses on the practical applications of the safety approach developed in the previous parts of the project.

Implementing Geological Disposal of radioactive waste-Technology Platform (IGD-TP) concentrates on initiating and carrying out European strategic initiatives regarding the geological disposal of radioactive waste. The aim is to address the scientific, technological and social challenges remaining and supporting European waste management programmes. IGD-TP provides two routes for collaboration projects, either through the WMO college of EURAD or as a member of IGD-TP projects when enough interested participants are found. COVRA ensures the link with ERDO in IGD-TP to enhance visibility also for ERDO projects in EURAD.

COVRA participates and co-funds participation of research organisations in EURAD projects ACED WP3, DONUT WP2, FUTuRE WP4a, GAS WP4a, ROUTES WP1, UMAN WP3 more detailed description of the work content can be found in following chapters.

Task 0.3: Programme development for continuity

As the research programme is intended to be long-term, the programme should be updated and adapted every five years. Content-wise this is arranged through five-year work programmes (see Chapters 4 and 5 for the current work programme).
This work is covered in the current task and led and performed by the programme office with advice from the IAB and - if needed - with external assistance.

The work programmes contain the plans for research activities and production of the safety cases for five years. Each work programme will be structured with work packages and tasks: the work packages in the current work programme are designed so that, in principle, only their tasks should be updated in future work programmes. In the fourth year of each work programme a start is made with the development of the work programme for the next five years. This may also include changes in the overall framework of the long-term research programme, to incorporate lessons obtained or changes applied during the first five years.

Task 0.4: Expert advice to the programme director and programme office

Both the programme director and programme office can request experts' advice from the International Advisory Board (IAB). The IAB, its members and role has been introduced in section 3.3. This task is intended to assure the quality of the research programme and its outputs, assure its international embedment and its linking with adjacent initiatives in the Netherlands and abroad, and to strengthen the research programme based on input from international experts.

Underground Research Laboratory at 230 metres depth in Belgium in poorly indurated clay (Boom Clay). Source: EIG EURIDICE.

4. Content of the programme for 2020-2025: Strategic research topics and production of safety cases

Higher level strategic research topics such as multinational solution, reversibility/retrievability, costing and integration of knowledge, gained during this research programme, for production of safety cases, as well as research topics covering assessment of the disposability of each type of waste, will be described in this chapter. For each task we have indicated its priority for the programming period 2020-2025. For projects with a high priority (1 and 2) funding has been secured at the start of the programme. Projects with lower priority will be funded if funding is left or additional (co-)funding is acquired during the first programming period.

4.1 Work package 1: Programme strategy

Higher level strategic/cross-cutting research topics, such as multinational solution, reversibility/ retrievability and costing, which are largely independent of the geological disposal system (Chapter 5) are described here. Projects in work package 1 provide information for strategic decisions (e.g. shared solution), comparisons between different solutions (e.g. clay vs. salt) and provide feedback or aid to safety cases.

Task 1.1: Overview of alternatives for national geological disposal facilities - Priority 1

In this task, the results of shared repository projects are summarised and compared to the national GDF options in rock salt and poorly indurated clays. Conclusions from the point of view of national strategy/requirements are also reported. Input for this task is provided by Task 1.2: Routes to multinational GDF implementation - Priority 1, Task 1.5: Deep Borehole Disposal - Priority 2 and national GDF studies performed in WP2.

The expected outcome of this task is a comparison (e.g. feasibility, requirements, costs) between a shared repository and national repository options.

The results are to be published in a COVRA report (Disposal solutions report).

Task 1.2: Routes to multinational GDF implementation - Unique opportunity

About half of the EU Member States considers shared Radioactive Waste Management (RWM) disposal solutions. However, the only presently ongoing shared solution in Europe, is the Belgium agreement to manage very small quantities of radioactive waste from the Grand Duchy of Luxembourg (Nirond 2019). A core issue with shared RWM solutions is how to move from concept, to project establishment and through to facility siting and operation. Although the steps are almost identical to those for any national facility, the multinational dimension adds further complications. Using one or more practical case studies it can be shown how participating Members States can work together to establish a route through these steps. Also, possible R&D needs are defined.

Questions to be answered are:

- What are the knowledge and approaches to share technologies and facilities between Members States?
- What are the interests in and experiences with sharing technology/facilities in the different steps of waste management of Member States?
- What are the needs for R&D, strategic priorities and opportunities for collaboration between Member States?

These topics are handled in Task 6 of the ROUTES Work Package of the EURAD project and results are reported in ROUTES deliverable(s).

This task gives input to Task 1.1: Overview of alternatives for national geological disposal facilities - Priority 1.

Task 1.3: Synthesis of knowledge on improving cost estimates and cost optimisation – Unique opportunity

A cost estimate comparison will be made for a GDF in rock salt, poorly indurated clays and alternatives for national geological disposal facilities using the SSK method. Quantifying the costs of radioactive waste management, especially of disposal, and estimating how these costs may arise over long periods of time (up to several decades) is a complex and sometimes politically sensitive issue. COVRA will update cost estimates for GDFs in poorly indurated clays and rock salt and the cost estimate for a shared disposal facility from ERDO's cooperation project.

Expected outcomes are:

- A review of national costing information for disposal, including a comparison of costing methodologies and underlying assumptions used by national strategies and programmes (ERDO)
- A review of existing studies on cost estimates for multinational storage and disposal of radioactive waste (ERDO)
- A cost estimate update for a GDF in poorly indurated clays (COVRA)
- A comparison of cost estimates for national GDFs in poorly indurated clays and rock salt and a shared multinational disposal facility (COVRA)
- An assessment of the potential of, and specific savings by, sharing facilities for final disposal (ERDO)

An ERDO initiative will prepare a report on this issue from a multinational perspective. COVRA reports will be prepared on GDFs in rock salt (in Task 1.7: Disposal concept and cost estimate for a GDF in rock salt – Priority 1) and in poorly indurated clays (in this task). A summary report will draw conclusions based on the combined results of these reports.

Task 1.4: Common approach to acceptance to a disposal facility - Unique opportunity

Nuclear activities performed in the past have generated a significant number of radioactive waste streams which have been treated and conditioned according to the rules in force at that time or simply stored pending a suitable management solution. These waste streams (conventionally called 'Legacy Waste') are often lacking sufficient physicochemical-radiological characterisation data for defining possible re-treatment/re-conditioning processes in line with current regulatory requirements and/or checking compliance with Waste Acceptance Criteria (WAC) of storage/disposal facilities. The ERDO initiative, the information exchange project LWC 'Legacy Waste Characterisation for possible acceptance to a disposal facility', aims to share this missing data or methodologies for waste characterisation. These issues are also dealt with in EURAD WP ROUTES, especially in tasks 2-4 and information sharing between ERDO and ROUTES is planned.

Results are expected to provide:

- Identification the main Legacy Waste streams (in interested countries) for which characterisation data are missing (ERDO)
- A survey of the available WACs or preliminary WACs to establish a minimum common set for waste acceptance (ERDO)
- Collection of the main properties of typical ILW packages suitable for disposal based on available conceptual Disposability Assessment (ERDO)
- Identification of the minimum set of characterisation data for disposal to a National or Multinational Disposal Facility (ERDO)
- Identification of characterisation techniques for radioactive waste (ERDO, ROUTES)
- A comparison of characterisation methods (ROUTES)
- An analysis of existing approaches and identification of knowledge gaps (ROUTES)
- An overview of the current application in member states of WAC at different stages in the waste lifecycle (ROUTES)
- Identification of R&D needs and opportunities for collaboration between interested parties (ROUTES)

The results will be published in ERDO and ROUTES deliverables.

Task 1.4.1: Common approach to disposability assessment - Priority 4

One of the problems facing Small Inventory Member States (SIMS) is that, without some concept of how the waste might eventually be disposed, it is not possible to move forward with programmes for conditioning and packaging wastes. Consequently, wastes might today be packaged only for storage, while they could already be packaged and conditioned for disposal – thus saving additional costs and handling risks. Using information (e.g. from EURAD-WP ROUTES) on SIMS inventories and possible Small-Scale Disposal (SSD) solutions, a common approach to 'disposability assessments' can be developed. This common approach is a set of simple performance and safety assessments for each of the SSD options.
The results will allow each of the SIMS to make decisions on possible storage and disposal routes and will assist with provision of waste packaging advice to small users and the development of waste acceptance criteria for the SSDs.

Outcome of this task:
A set of simple performance and safety assessments for each of the SSD options.

This task can be seen as a continuation of Task 1.4: Common approach to acceptance to a disposal facility - Unique opportunity and will be performed if resources or opportunities for collaboration appears during this research programme.

Task 1.5: Deep Borehole Disposal - Unique opportunity

The goal of the deep (several kilometres) borehole disposal project is to develop potential borehole disposal solutions that could handle all or most of the higher activity and longer-lived wastes in one or more actual national inventories. This ERDO project will investigate and propose concrete technical solutions, including use of existing borehole technology, the need to develop new methods, waste packaging options for borehole disposal, depth of the borehole for the different waste types and packaging of the wastes, costs etc.

The project would use country-specific data to develop a potential national Borehole Disposal (BD) design and management solutions. The following topics are in the scope of this task:

- Identify the type and volume of the country's inventory of radioactive waste that could be suitable for a national BD
- Identify the dimensions and inventory of the waste packages to be disposed of in the BD
- Identify design and operating concepts of BD facilities that would suit national inventories and develop country-specific scenarios for how BD might be implemented
- Assess strategic implications of incorporating BD into national disposal planning
- Identify which other facilities would be needed in the national strategy
- Consider how inclusion of BD might affect timing of storage and disposal planning
- Assess cost implications of using BD
- Evaluate the strategic and design scenarios developed above
- Identify the need for further R&D

The outcome of the project will be a conceptual feasibility study of borehole disposal with actual national inventories (selected from ERDO participants).

The ERDO initiative will report the results of this study. The results of this task are input for Task 1.1: Overview of alternatives for national geological disposal facilities - Priority 1.

Task 1.6: Reversibility/retrievability - Priority 3

The technical feasibility of the reversibility requirement during operation and of recoverability at post-closure has to be proved. Suitable monitoring measures have to be developed and influences on design and concepts have to be investigated for possible disposal methods. For some disposal activities (e.g. deep borehole disposal, shared solutions) the demand of reversibility might be more difficult to guarantee than for a national GDF. To be able to assess retrievability (i.e. means to achieve decision of reversibility) in more detailed than already done in the Netherlands, a more detailed design of the GDF is needed. Hence, the handling of this issue mostly concentrates on the reversibility requirement and its impacts on alternative solutions.

Task 1.7: Disposal concept and cost estimate for a GDF in rock salt - Priority 1

Task 1.7.1: Cost estimate for a GDF in rock salt – Priority 1

In the Netherlands, COVRA is the organisation that is responsible for managing radioactive waste from collection up to final disposal in a GDF. Although an operational repository is foreseen in 2130, steps for the longer term are already taken. This includes conducting, both internally and externally, research on disposal and to ensure that enough funds will be available to do the necessary research and to construct, operate and close a GDF. As in many other countries, all these costs are paid by the waste producers via fees collected by the WMO. To ensure that the current and future fees will cover all costs, it is essential to estimate periodically the cost of a GDF based on the latest insights.

A cost estimate for a GDF in rock salt was done in the OPLA programme (1982-1992). In this programme, it was estimated that the development of a GDF, would cost 454 million Dutch Guilders (or about 206 million euros) based on the price level of 1985. A more recent cost estimate was made in 1999. It was then estimated that the total cost for a GDF in rock salt would be 280 million euros and an additional 1.8 million per year would be required to keep the GDF open (Grupa and Jansma, 1999). Note that this estimate was only for the disposal of HLW. Thus, the latest cost estimate for a repository in rock salt in the Netherlands is over 20 years old.

As techniques and insights have evolved and previous costs did not include disposal of Low and Intermediate Level Waste (LILW) and (Technically Enhanced) Naturally Occurring Radioactive Materials ((TE)NORM), an updated cost estimate for a repository in rock salt is needed using the SSK cost estimate method (Verhoef et al., 2017). It is also of interest to know what the different phases (construction, operational and closure phase) and components (vertical tunnels, disposal galleries etc.) will cost individually, in order to enhance and optimise the GDF and to identify the areas with the largest uncertainties in costs.

This work package should thus result in a cost estimate for a GDF in rock salt. This estimate should be made by or in cooperation with an organisation or company that has hands-on experience with a disposal facility in rock salt.

What is the total cost for building a GDF in rock salt, based on the SSK method, and what is the cost for the different components of the GDF (e.g. vertical tunnels, disposal galleries etc.)?

Task 1.7.2: Review of different disposal concepts in rock salt - Priority 1

Before a new cost estimate for a GDF in rock salt can be made, it is necessary to review and identify the (dis)advantages of the different disposal concepts for a GDF in rock salt. This review should take into account, but not limited to, the long-term safety (cf. Task 3.3.1: Waste package for HLW - Priority 2 and Task 3.3.2: Waste package for (TE)NORM – Priority 2) and the operational phase (e.g. how easy is it to emplace the waste cf. Task 3.3.1: Waste package for HLW - Priority 2); how much maintenance will be needed and how can it be minimised; how much time will be needed for construction). Based on this review, a generic disposal concept will be selected, optimised where possible and used for input for the cost estimate.

This work package should preferably be done by or in cooperation with an organisation or company that has hands-on experience with a disposal facility in rock salt.

Select, based on an extensive review, a generic disposal concept and optimise it when possible. This selected disposal concept is used to make a cost estimate for a GDF in rock salt.

4.2 Work package 2: Safety case and integration

The currently most widely accepted description of a safety case for geological disposal is formulated by the IAEA in 2011 and reproduced in the 2013 NEA update. The concise definition used e.g. in OPERA is from the IAEA Safety Standards for Geological Disposal (IAEA 2012).

"The safety case is an integration of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the geological disposal facility".

Safety cases can be made at various stages in a repository development programme, in an iterative process. Here non-site-specific safety cases for indurated clays and rock salt are developed using latest available scientific and technical information gained during this research programme. The safety cases developed and the information obtained during this programme will guide the planning of the next phase of COVRA's research programme. The safety cases will contribute to maintaining the relevant knowledge and to potentially modifying some of COVRA's current activities.

The disposal of every type of waste that COVRA currently stores, needs to be assessed. The waste content, treatment and conditioning all have an influence on the durability of the waste packages in the GDF, potential release mechanisms and interactions with the host rock. So far, the waste acceptance criteria defined by COVRA were developed mostly to ensure safe transport, treatment and storage with the assumption that requirements for long-term storage will be analogous to those for geological disposal.
The waste package should prevent or reduce potential transport of radionuclides into the human environment. The waste package should provide for a stable containment of the radionuclides and allow retrievability. Sometimes, however, disposal poses different requirements. Whereas, for example, the safety of transport, treatment and storage is in particular determined by the short-lived radionuclides, the safety of geological disposal is determined primarily by the long-lived radionuclides, since the others will decay to insignificant levels within the GDF. Many of these long-lived radionuclides are difficult to measure by means of the commonly used gamma-spectrometry of the delivered waste packages.
It is thus important to collect information on such nuclides when the waste is generated and processed. If not properly collected and documented upon generation and treatment, it will be difficult to trace back information about the waste at the time of disposal.
An assessment of the disposability of each type of waste that is currently stored at COVRA's premises should lead to these additional waste acceptance criteria. These criteria are defined on the waste characterisation performed for geological disposal. A start has been made in OPERA to obtain this waste characterisation, especially for more unfamiliar types of waste such as spent research reactor fuel (Verhoef, et al. 2016).

Task 2.1: Safety case development for a GDF in rock salt - Priority 1

There are currently three deep geological repositories in rock salt: two in Germany and one in the USA. In Germany, two old salt mines in domal rock salt (Asse and Morsleben) have been used for the disposal of radioactive waste. Although both the Asse and Morsleben mine do not adhere to the current high international safety standards for a GDF in rock salt, research in Germany (past and current) is of high level and lesson learned from the past can and will be used in the future. For example, for the disposal of HLW, a new purpose-built GDF rather than the reuse of old salt mines is currently envisioned in Germany.

The deep geological repository in the USA, the Waste Isolation Pilot Plant (WIPP), is the only repository in rock salt that is currently operational. For the WIPP, a site was selected in 1974 and construction started in 1984. The first nuclear waste, transuranic waste produced as by-product of the nuclear defence programme in the USA, was emplaced in 1999. Prior to the site selection for the WIPP, knowledge and understanding of the behaviour of the GDF had achieved a sufficiently mature level.

The same level of knowledge has to be achieved in the Netherlands by 2100 to make a choice between poorly indurated clays and rock salt as host-rock. To attain this level of knowledge, the knowledge developed over time in the Netherlands and in other countries (e.g. Germany, USA, Romania and the UK) will be integrated in the Dutch safety cases and post-closure safety assessments. The Dutch safety cases will also benefit from international collaboration via the Salt Club, DECOVALEX and other (informal) collaborations.

Although much knowledge has been developed in other countries, COVRA will fund, co-fund or participate in specific research programmes to fill knowledge gaps that reduce physical and chemical uncertainties. This includes laboratory experiments, in-situ experiments performed by other organisations and the use of stored rock salt cores. With a better knowledge of the geotechnical and geochemical properties of the host rock and its evolution through time, the confidence in the outcomes of the safety assessment will increase.

Task 2.2: Integration of knowledge on rock salt - Priority 1

Following the definition of the safety case from the IAEA Safety Standards for Geological Disposal, the initial safety case for rock salt will integrate arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the GDF. This initial safety case for rock salt will demonstrate how radioactive waste can be safely disposed in rock salt in the Netherlands. It is expected to be ready in the first quarter of 2024 to allow the regulator sufficient reading time for its reporting duty in 2025 to the European Commission (EU 2011).

As the first initial safety case for rock salt in the Netherlands, it will follow closely the outline of the OPERA initial safety case for poorly indurated clay (Verhoef et al. 2017). Therefore, the initial safety case in rock salt will start with a very short general introduction to familiarise the Dutch audience with the concept of a GDF, followed by the waste expected to be disposed, an overview of the different barriers (host rock and engineered barrier) and the safety assessment.

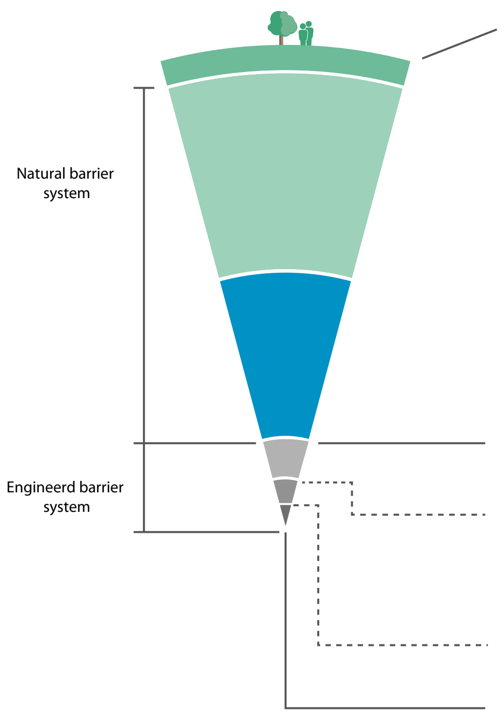
The introduction will explain why geological disposal is needed, will refer to the current research programme and will present the outline of the initial safety case for rock salt. Since research on geological disposal in rock salt has started in the 70s (Hamstra 1976), the introduction will also encompass a short overview of the different Dutch research programs in the past. This will include the proposed disposal concepts of the past. Also, a short overview will be given of the different disposal concepts in rock salt in other countries, like USA and Germany, and how the current Dutch concept differs from the Asse mine.

Next, an overview will be given of the different types and volumes of waste destined for geological disposal. An updated disposal concept in rock salt, including potential variants and their (dis)advantages, will be presented to store this waste. Based on the updated concept, the total cost and cost per segment of the GDF (e.g. tunnel, waste package, cf. Task 1.7.1: Cost estimate for a GDF in rock salt - Priority 1) will be given. A short description of the waste packages intended to be used for HLW (cf. Task 3.3.1: Waste package for HLW - Priority 2) and (TE)NORM (cf. Task 3.3.2: Waste package for (TE) NORM - Priority) will also be presented.

This will be followed by a description of the different barriers within the GDF, the assumptions made for their role, the remaining uncertainties, and further work. It will start with a generic overview of the overlaying geological layers. This will be relative short as the focus of this initial safety case will be on the host rock and engineered barrier. Then the host rock will be addressed, which will include an overview on the different salt (bedded and domal) formations in the Netherlands and their distribution based on seismic sections and boreholes when applicable (cf. Task 4B.4.1: Bedded salt of the Röt formation - Priority 1) and the availability of brine in rock salt (cf. Task 4B.2.3: Brine availability - Priority 1).
The host rock is followed by describing the engineered barrier, which includes the granular backfill and how its permeability evolves over time with significant gas production (cf. Task 4B.2.1: Gas Production - Priority 2 and Task 4B.2.2: Gas-Rock Salt interaction - Priority 3) or without significant gas production (cf. Task 4B.2: Evolution of the permeability-porosity in rock salt - Priority 1), the waste packages used for the different types of the waste intended for disposal (cf. Task 3.3.1: Waste package for HLW - Priority 2 and Task 3.3.2: Waste package for (TE)NORM - Priority) and the seals within the GDF.

The safety assessment is the backbone of this initial safety case for rock salt. A safety assessment quantifies the behaviour of both the natural and engineered barriers and calculates the potential releases of radionuclides from the waste into the biosphere, potentially resulting in the exposure to humans. Like in the initial OPERA safety case (Verhoef et al. 2017), the exposure will be compared with a yardstick e.g., a dose constraint. The safety assessment in rock salt, having the goal to demonstrate that a GDF in rock salt is safe, will encompass a normal and disrupted evolution. In both scenarios, the engineered barriers, host rock and their evolution over time (cf. Task 3.3: EBS for rock salt - Priority 2, Task 4B.1: Geotechnical properties - Priority 1 and Task 4B.2: Evolution of the permeability-porosity in rock salt - Priority 1), the transport of radionuclides (cf. Task 4B.2.3: Brine availability - Priority 1 and Task 4B.3: Radionuclide Solubility in Brine - Priority 1), the surrounding rock formation, and natural processes that could potentially disturb (cf. Task 4B.4: Geological setting – Priority 1 and Task 5.1: Impact of tunnel valleys - Priority 3) a GDF must be considered.

For this non-site-specific safety assessment, the focus will be on the host rock, the engineered barriers and transport of radionuclide as shown in Figure 11. In this safety assessment, realistic information will be used when available, while conservative assumptions are used when no information is available. Then, the sensitivity of the safety assessment to the used realistic and conservative information will be analysed. This approach is expected to enhance the effectiveness of the programme – for example by avoiding costly over-engineering of system components of the GDF – and will help to identify future work. This safety assessment will benefit from the work done in EURAD (cf. Task 2.2.1: Development/improvement of numerical methods & tools for modelling coupled processes - Unique Opportunity and Task 2.2.2: Methodological approaches to



Component	R&D effort for the next safety case
Biosphere	Very limited R&D effort. Integration of available information of the IAEA will be used for the safety assessment.
Surrounding rock formations	Limited R&D effort. Integration of the available knowledge on the formation of tunnel valleys potentially disturbing a GDF and changes in ground water that could effect the rate of subrosion and transport from host rock to the biosphere.
Host rock: Rock salt	**Geotechnical properties** Large R&D effort: More data on rock salt increase understanding of itslong term evolution and decreases the uncertainties. **Evolution of the permeability-porosity in rock salt** Large R&D effort: There is still a large uncertainty on the long-term evolution of the granular backfill. Provides input for the requirements on the engineered barriers / waste package. **Radionuclide Solubility in Brine** Large R&D effort: Brine is a potential transport medium for radionuclide but limited information is available on its availability. **Geological setting** Moderate R&D effort. More information on bedded salt of the Röt formation will focus research in the future.
Repository	Limited R&D effort: Relevant information is available in the Germany and USA on seals that could be used in the Dutch case.
Waste package	Waste package for HLW: Moderate R&D effort. Repackaging of HLW waste possibly needed to provide containment when backfill and EDZ still have a significant permeability. Waste package for TE(NORM): Moderate R&D effort: epackaging of waste possibly needed for to have a waste package suited for high - saline environment.
Waste form	Limited R&D effort. Integration of available information from different sources

The focus of the research on the geological disposal system is on the host rock (rock salt) and the engineered barrier system. Or more specifically for rock salt, indicated by the red rectangle, the host rock and the waste package for HLW and (TE)NORM although others will. Note that the names in the figure correspond with the subtasks in the research programme, indicates the research effort and, very shortly, the reasoning why these subjects are important.

Figure 11: Coherence between tasks, the geological disposal system and the initial case for rock salt

uncertainty and sensitivity analysis - Unique Opportunity). The next safety cases, and hence safety assessments, will use more realistic values for both scenarios going towards a more realistic evolution of the GDF in rock salt and will, with time, include processes that occur in surrounding rock formation, biosphere and society.

The last chapters will give a summary and an outlook to the next work programme of the research programme.

Task 2.2.1: Development/improvement of numerical methods & tools for modelling coupled processes - Unique Opportunity

In the last decades, computational power has grown exponential. Equally, the complexity of numerical models has grown, and numerical models can thus still take days or even weeks to complete. Besides increasing computational power even further, numerical techniques can be further optimised to reduce the computational power required.

In this work package, emplaced within DONUT and part of EURAD, COVRA will prepare benchmarks from the point of view of implementors and evaluators. The prepared benchmarks will help to quantify how numerical methods developed in DONUT are relevant regarding currently used methods, and to compare tools in which these methods are implemented. These benchmarks will be derived mainly from EURAD work packages, for example GAS, and will be used to quantify the efficiency and added value of the numerical methods in terms of: (1) the increase of knowledge, (2) accuracy, (3) robustness, (4) computational cost, (5) robustness of scale-transition approaches, and (6) the ability to manage uncertainty and sensitivity analyses.

By participating in this work package, COVRA can keep up with how other participants approach problems with numerical methods and handle uncertainties in their data. This work package is co-funded by the European Commission and offers a unique opportunity to keep up with new developments and insights in numerical methods and tools for modelling coupled processes.

Prepare benchmarks that will help to quantify how numerical methods developed in the DONUT work package, as part of EURAD, can improve calculations (e.g. enhance accuracy and reduce run times).

Task 2.2.2: Methodological approaches to uncertainty and sensitivity analysis - Unique Opportunity

Numerical models play a vital role in safety assessment. To addresses the sensitivity (contribution of the inputs to the total uncertainty) and uncertainty (uncertainty in model outputs that derives from uncertainty in inputs) in the safety assessment, a variety of mathematical methods are available.

The goal of this task is to investigate how typical numerical safety assessment models can best be analysed in view of uncertainty and sensitivity with classical and modern methods and - where sensible - to coordinate, initiate or recommend the development of appropriate computational tools.

This task is part of the international UMAN project, which is co-funded by the European Commission. COVRA will participate in technical meetings, share experiences about uncertainty and sensitivity analysis methods and will review the deliverable.

This task offers COVRA a unique opportunity to keep up with how other participants address sensitivity and uncertainty in numerical models and keep up with new developments and insights in this field. This task will contribute to the safety assessment and the analysis of the sensitivity and uncertainty of a safety assessment.

Investigate how typical numerical safety assessment models can best be analysed in view of uncertainty and sensitivity with classical and modern methods.

Task 2.2.3: Uncertainties related to human aspects - Unique Opportunity

Uncertainties do not only exist in numerical models, but also stem from humans. These encompass a wide variety of uncertainties and have different origins like, for example, politics (e.g. continuation of the radioactive waste policy), governance (e.g. how should we consider the interests of the various actors?) and finance (e.g. will the necessary funds be available?).

In this task, we address the identification, characterisation, evolution and significance of uncertainties associated with social, economic and other human aspects identified as being relevant to safety and the decision-making process. The expert group, of which COVRA is part, will first identify and characterise uncertainties based on available information from national programmes and international initiatives and relevant past European RD&D projects for each stage of a repository (need for action, disposal concept, site selection and design, construction, operation, closure, post closure institutional control, post closure passive control).
The expert group review will be completed, via a questionnaire, with information from other EURAD participants. The result of this task will be a EURAD report. This project, part of UMAN, is co-funded by the European Commission.

Identification, characterisation, evolution and significance of uncertainties associated with social, economic and other human aspects identified as being relevant to safety and the decision-making process.

Task 2.3: Safety case development for a GDF in poorly indurated clays - Priority 1

Figure 9 showed the cycle that will be run for the next decades to make non-site specific (generic) safety cases e.g. those for a GDF hosted in poorly indurated clay.

The foreseen safety cases of a GDF in poorly indurated clay will benefit from research performed in foreign countries, especially countries with GDFs in clay. Switzerland, France and Belgium have chosen to build their GDFs in argillaceous formations and are selecting sites or have selected a site since their knowledge and understanding of the behaviour of the GDF has achieved a sufficiently mature level. By 2100, this level needs to be achieved in the Netherlands in order to make a choice between host rocks. The speed to attain this mature level for a GDF hosted in poorly indurated clay in the Netherlands may be slower than in these countries, since the Dutch resources to spend on the required research is significantly less. However, a lot of the developed knowledge from these countries can be integrated in Dutch disposal concepts and post-closure safety assessments.
The identification of uncertainties in the behaviour of their disposed waste has been done by these three countries and the expenditure of research is transferred from non-site-specific research towards

site specific research. But sometimes, further argumentation of the chosen approach is requested by which non-site-specific research is still performed. In these occasions – that are expected to become rarer in the next decades – COVRA can participate and/or co-fund organisations if the research is expected to identify white spots in the Dutch safety case or to reduce physical and chemical uncertainties. The main effort is devoted to selecting the relevant material from these programmes for the Dutch case.

A lot of assumptions have been made in the post-closure safety assessments and evaluations of the construction and operational feasibility in the previous research programmes CORA and OPERA. Especially the assumptions made for the host rock require evidence to increase the confidence on the outcomes of these evaluations and assessments. In the next decades, no dedicated drilling programme is foreseen. But almost all required geotechnical and geochemical properties need to be experimentally determined from fresh poorly indurated clay cores that have been sampled from relevant Dutch disposal depth. COVRA therefore participates in drillings that have been initiated for another reason than geological disposal of waste.

Finally, the radiological consequences of all events expected in a normal evolution of the disposal system will be calculated. All potential what-if scenarios for altered evolutions will be evaluated.

Task 2.4: Integration of knowledge on poorly indurated clays - Priority 1

The first three chapters in the initial Dutch safety case familiarised the Dutch public with geological disposal and a start was made with the safety strategy (Verhoef et al. 2017). The other chapters had a specific focus on the waste characterisation and Boom Clay, since this host rock is available at suitable disposal depth in the Netherlands. This host rock has not been investigated to the extent of rock salt and much could be learned from the Belgian programme. Although the research budget for Boom Clay has until now been less than a third of the budget that has been available for rock salt in the previous Dutch programmes, the integration and collection of information in this initial safety case has been well made in order to further develop the safety case for a GDF in poorly indurated clay.

A further non-site-specific safety case will be developed with an integration of the latest available scientific and technical information into a conceptual understanding and a quantification of the behaviour of engineered and natural barriers. This safety case will demonstrate how and why disposal of Dutch radioactive waste in poorly indurated clays can be implemented safely. It is envisaged to be ready in 2023 or in the beginning of 2024 in order to allow the Ministry of Infrastructure and Water Management sufficient reading time for its reporting duty to the European Commission in the framework of the EU waste directive (EU 2011).

The backbone of a safety case is a safety assessment. This assessment quantifies the behaviour of natural and engineered barriers to calculate potential releases of radionuclides from the waste into the accessible human environment and the resulting radiation exposures. The radiation exposures are then compared with a yardstick e.g., a dose constraint.

The information needed to quantify the behaviour of the barriers is varied and is subject to different types and levels of uncertainty. In the initial Dutch safety case, realistic information available on system understanding was compared with conservative assumptions made in the safety assessment. A balanced view between realism (somewhere close to the expected behaviour) and showing robustly and simply that the system is safe, even with built-in conservatism, is necessary to make informed decisions later in the programme. These concern GDF design optimisation and, eventually, on acceptable site characteristics. This approach is expected to enhance the effectiveness of the programme, for example by avoiding costly over-engineering of system components or rejection of acceptable GDF sites.

The next safety assessment is therefore focussed on understanding of the disposal system in order to make a best estimate of the normal evolution. The impact of neglecting the expected behaviour of the EBS interacting with the host rock will be highlighted and the impacts of the two main events that may induce advective migration of radionuclides in the host rock will be assessed. Figure 12 shows the coherence between the tasks described in the next chapter, especially those executed in collaboration with external organisations, for the disposal system containing a GDF in poorly indurated clay. It also shows some features that are not included in the safety assessment performed in OPERA (2011-2017) but will be included in the safety assessment in the next safety case.

The waste package for the two heat generating HLW-families, spent research reactor fuel (SRRF) and CSD-v, has been adopted from the Belgian programme in the previous safety case. The safety strategy for this waste package is not changed, but in the next safety case the chemical evolution of the concrete in this waste package will be calculated in order to determine the potential period in time for passivation of the carbon steel overpack and the expected chemical conditions when there is contact between pore water and the waste form. The required thickness of the concrete for sufficient shielding will be calculated for Dutch specific storage times. The emplacement methodology of these large waste packages will be evaluated as well as the impact on the dimensions of the tunnel galleries. The waste form of CSD-v is also evaluated in a European collaboration in which COVRA participates: ACED (cf. WP3). The waste package as well as the waste form of SRRF contains metals. Anaerobic conditions are expected in the post-closure evolution and water will act as an oxidant to corrode these metals. The potential gas generation has not been included in the safety assessment in the initial safety case but will be included in the next one. Criticality of SRRF will at least be looked at but a quantitative analysis might require additional funding.

Also, non-heat generating HLW, ILW in IAEA terms, was proposed to be encapsulated. This may not be necessary. The next safety case will show this evaluation, including the potential effect of gas generation of the waste forms.

Although a site will not be selected in the Netherlands, some essential characteristics for the post-closure safety assessment can be given. Sites at which the pore water flow through the clay host rock is limited on the long-term and sites that possess reducing conditions are considered suitable. These two simple characteristics limit the potential radionuclide transfer from the host rock to the surrounding rock formations e.g. the redox sensitive radionuclide solubility is smaller at reducing conditions. Another characteristic, specific to the geographical location of the Netherlands, is the salinity of the clay pore water. The brackish water interface is less than 200 metres in most of the Netherlands. Consequently, the dissolved organic matter content is limited in clay host rock pore water. These three characteristics will be used in the chemical evolution of the engineered barrier system as well as the potential radionuclide transport by the generation of gasses in the EBS. Especially the migration of uranium is expected to be different from the studies performed in OPERA with inclusion of these three characteristics.

Results from COVRA's participation in a European collaboration: GAS (cf. WP4A) are used in the next safety case. The results obtained by BGS and TU Delft can be used, provided results become available before 2023. The potential new insights can for sure be used for the safety case thereafter for the evaluation in 2035.

The evaluation of the feasibility of the concrete liner facility in OPERA indicated that there is insufficient data on Dutch geo-technical properties of poorly indurated clays. WP4A shows the gathering of these data in this programme as well as collecting the required information.

Given the available budget, research on the surrounding rock formations and biosphere is limited and information from the previous research programmes and international literature e.g. IAEA BIOMASS will be the primary sources for the next safety case.

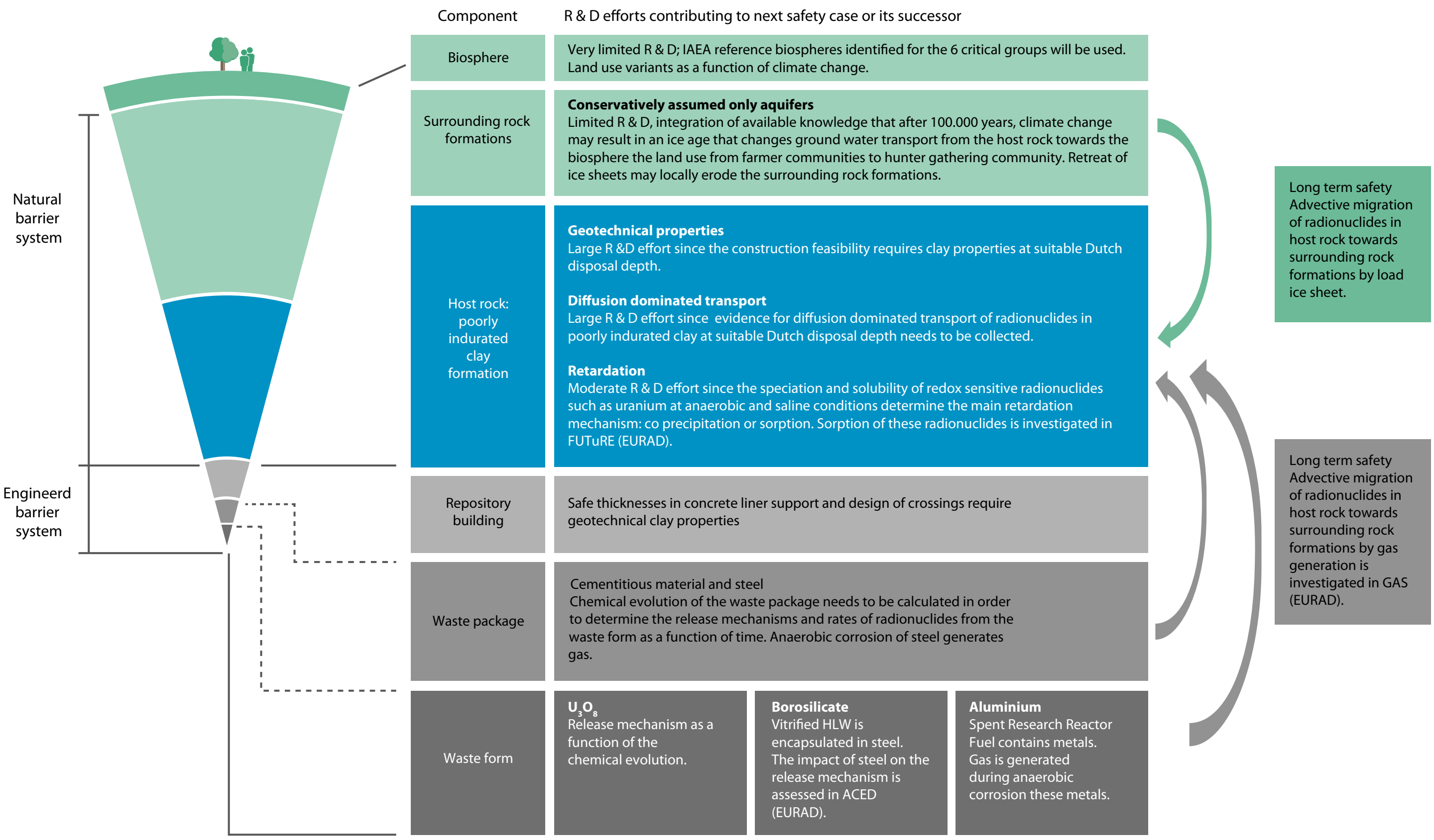


Figure 12: Coherence between tasks, the geological disposal system and the updated safety case for poorly indurated clays

A concrete liner as an engineered construction for an underground facility in poorly indurated clay (Boom Clay). The facility remains dry by ventilation.
Source: EIG EURIDICE.

Inside ONKALO®, the underground rock characterisation facility in Olkiluoto, Finland. Source: Posiva Oy.

Unloading radioactive waste that is stored safely inside the yellow container.
Source: COVRA.

What do we need to know now?

5. Content of the programme for 2020-2025: research on the geological disposal system

The research programme is directed at realising updated safety cases for a GDF in poorly indurated clays and rock salt. These are the host rocks in which the GDF will be constructed. The geological disposal system, however, extends beyond the host rock and the GDF. It consists of components that act as natural and engineered barriers between the radioactive waste and society.
The components of the geological disposal system are depicted in Figure 13. The work packages in this chapter are related to the components of the geological disposal system.

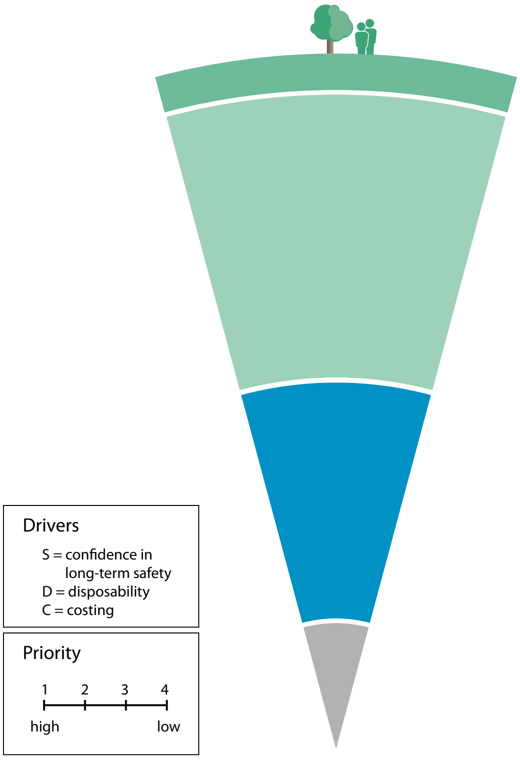
Safety is a central concept in the research programme. The required level for a GDF will be determined by national and international regulations and guidelines. However, the question what level of safety is acceptable is determined by societal processes and must be provided by the containment and isolation of the different barriers in the disposal system. For a GDF in poorly indurated clay, the current knowledge on the performance and evolution of compartments of the evolution and their contribution to safety has been assessed in the OPERA Safety case. Some safety relevant features for a GDF in rock salt have been identified (Verhoef et al. 2017). Based on that assessment, the key topics for future research were extracted and Figure 13 shows the key topics for each component in the disposal system that is discussed in more detail later.

5.1 Work package 3: Engineered barrier system

The engineered barrier system (EBS), which provides both physical and chemical containment of radionuclides in the waste, is protected by the host rock and surrounding rock formations from dynamic natural processes out into the far future, even allowing for impacts of future developments including climate change.
Any potential radionuclide transport from the waste towards our living environment requires water or gas.

Undisturbed rock salt exhibits a very low permeability and is impervious (i.e. no or very limited interconnected pore space) to liquids and gasses. The potential migration paths for radionuclides are therefore not within the host rock salt but the access shafts, tunnels and galleries necessary to emplace the waste packages. Another potential pathway for the migration of radionuclides is the excavation damage zone (EDZ) an inevitable feature close to the excavated area in rock salt. The plugs and seals to close the GDF have therefore an important containment function.

Poorly indurated clay host rocks also ensure little or no movement of water in the GDF. Some decades after the closure, the whole EBS will essentially comprise stagnant waters in a heterogeneous barrier system with interconnected porosity, where chemical reactions are mediated by slow diffusion of chemical species through the pore water. This different characteristic in host rocks requires a different EBS.



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

Figure 13: Key topics per component of the geological disposal system (Verhoef et al. 2017)

Task 3.1: Spent research reactor fuel - Priority 2

Spent research reactor fuel (SRRF) contains higher fissile concentrations than ordinary spent nuclear power fuel. The criticality of SRRF has unfortunately not been included in the safety assessment of OPERA, only the characterisation of this type of waste has been performed (Verhoef, et al. 2016). The second research programme CORA (1996-2000) has made a criticality analysis. For salt, the intrusion of water has been investigated with the assumption that the SRRF may be submerged in brine. The high chlorine content reduced the reactivity. For SRRF in clay, multiplication factors have been calculated. The SRRF amount per disposal package needs to be smaller than the SRRF amount in one canister stored at COVRA in order to keep this factor smaller than 1 (Dodd, et al. 2000). It therefore seems to be essential for the confidence in the post-closure safety to include criticality of this waste in the safety assessment. SRRF is a type of HLW that many European countries with small inventories have e.g. those without nuclear power plants and only nuclear research reactors.

How does the SRRF waste need to be conditioned for safe disposal?

External funding is needed for answering this research question in the next 5 to 10 years, as this task cannot be performed solely by COVRA. Research could be started earlier, if a collaboration can be established with other interested parties. This is a topic suitable for e.g. the ERDO initiative.

Task 3.2: EBS for poorly indurated clay - Priority 2 and 4

Task 3.2.1: Waste package for HLW - Priority 2

In OPERA, the waste package design for HLW has been adopted from the Belgian programme. The safety concept is that there can only be contact between pore water and the waste form when a temperature of the host rock poorly indurated clay is achieved at which nominal migration properties of radionuclides can be relied upon. This waste package consists of a steel overpack that is surrounded by a concrete buffer. The buffer provides the beneficial conditions to limit corrosion of the overpack for a sufficient long period in the post-closure phase.

This waste package also provides sufficient shielding; shielded containers are emplaced in the disposal galleries in order to have contact-handled waste in the operational phase. The required thickness for sufficient shielding in the operational phase supersedes the necessary thickness for the required period for the beneficial conditions in the post-closure phase. The necessary thickness for shielding can be reduced by using aggregate with a larger density. The use of depleted uranium in waste packaging for HLW and concrete liner needed for a GDF would also reduce the disposal volume significantly since the largest LILW volume to be disposed is depleted uranium. The use of depleted uranium as aggregates would reduce disposal volume and thereby the costs for the GDF significantly.

What are the necessary conditions allowing use of U3O8 stored at COVRA's premises as an aggregate in cementitious materials?

External funding is needed for answering this research question in the next 5 to 10 years, as this cannot performed solely by COVRA.

Task 3.2.2: Vitrified HLW - Priority 2

The European Project Assessment of Chemical Evolution of ILW and HLW Disposal Cells (ACED) aims to clarify which geochemical processes need to be included for representative assessments of the chemical evolution. The investigated geological disposal facilities are hosted in either crystalline or sedimentary rock types. Disposal cells containing vitrified HLW considered in this currently running EURAD Work Package. COVRA participates in ACED in order to identify which geochemical processes need to be included for the chemical evolution of disposal cell containing vitrified HLW in the cemented waste package, grout, concrete supported liner and poorly indurated clay host rock. This chemical evolution is used to identify the degradation mechanism and potential radionuclide release mechanism from the vitrified waste form and substantiation of the chosen degradation rate. The confidence in the post-closure safety is expected to be strengthening by inclusion of the chemical evolution in the safety assessment.

Task 3.2.3: Waste package for LILW - Priority 2

Disposal cells containing cemented ILW are considered in this currently running EURAD Work Package COVRA participates in ACED in order to seek which geochemical processes need to be included for the normal evolution of disposal cell containing cemented ILW. The confidence in the post-closure safety is expected to be strengthening by inclusion of the chemical evolution in the safety assessment and the waste package for disposal for ILW e.g. CSD-c may be optimised.

Task 3.2.4: Closure GDF - Priority 4

A stepwise closure is foreseen in which disposal galleries are filled with a grout after emplacement of waste packages in order to avoid circulation of water around the waste packages in the unlikely case of flooding during the operational phase. In the closing stage, bentonite seals are positioned at each disposal gallery in order to prevent the galleries from being a preferential pathway for radionuclides at any time in the post-closure phase. The access shafts and transport tunnels are expected to be mainly filled with excavated material. COVRA funding or co-funding of investigations in the closure of the GDF hosted in poorly indurated clay are not foreseen in the next 5 to 10 years since the confidence in the post-closure safety is expected to be negligibly enhanced and the costs for closure make up a small fraction of the total costs of the GDF.

Task 3.3: EBS for rock salt - Priority 2

Task 3.3.1: Waste package for HLW - Priority 2

There are two end-member options for the disposal of (heat-generating) HLW in a rock salt repository:

- In the first option, a thin (TORAD-B concept Poley, 1999) or even no (METRO concept, Heijdra and Prij, 1997) overpack is used for the disposal of the HLW. In this case, special equipment is needed for the emplacement of waste, but after emplacement the host rock provides the necessary shielding. The advantages of using a thin - or even no - overpack is that (1) the total weight of the waste package is limited, and (2) less foreign material is added to the GDF, making it thus (possibly) easier to understand the long-term evolution of the GDF.
- In the second option for the disposal of HLW in rock salt, a self-shielded "super" container is envisioned. This self-shielded "super" container is expected to provide complete containment until the backfill and EDZ has a negligible permeability. The time needed for the backfill and EDZ to gain a negligible permeability is determined in Task 4B.2: Evolution of the permeability-porosity in rock salt - Priority 1. This "super" self-shielded container has the advantages that it provides: (1) shielding during emplacement and retrieval of the waste, (2) all HLW fractions are enclosed in one standardised container (3) construction, assembly and quality assurance of a container can be done above ground. A self-shielded container (e.g. Pollox casks) has already been proposed in the German HLW repository concept in rock salt (Bollingerfehr, Buhmann and Filbert 2013). An other self-shielded super container, designed to provide complete containment for 1000 years beyond the early thermal period, has been proposed in OPERA (Verhoef et al. 2017).

Although some of the (dis)advantages of a "super" container have been identified, this task should first review the use of a self-shielded "super" container. This review should not only look at the long-term safety of the GDF, but also at the operational period (e.g. how easy is it to place the container and retrieve the waste) and the potential cost of such "super" container. Furthermore, the use of a "super" container should be compared (e.g. cost, long-term safety) to other possible engineered barriers like seals. If the use of a container has clear advantages, a self-shielded "super" container must be designed that provides complete containment during the period that the backfill and EDZ still have a significant permeability.

Note that this task will start after Task 4B.2: Evolution of the permeability-porosity in rock salt - Priority 1 is (nearly) finished, so that it can be used as input for this task.

What are the (dis)advantages of the use of a self-shielded "super" container? When it has clear advantages: design a self-shielded "super" container that provides complete containment during the period that the backfill and EDZ still have permeability.

Task 3.3.2: Waste package for (TE)NORM – Priority 2

Currently, (TE)NORM is at COVRA stored in standardised DV-70 containers. These standardised containers are suitable for above ground storage at COVRA. However, it is unclear whether the DV-70 container can be used in a GDF in rock salt or not. Thus, for a GDF in rock salt questions arise whether (TE)NORM waste must be repackaged for disposal in a high saline environment. And if so, what kind of containers can be used? Or: can the (TE)NORM be used in a different, more useful, manner? As (TE)NORM is expected to be the second largest volume of waste, answering these questions is important, as they will have an impact on the costs of the GDF in rock salt and the disposability of (TE)NORM. It is therefore essential to start with this task early in the research programme.

Can the standardised DV-70 be used in a high saline environment, which is expected in a GDF in rock salt? And if not, what kind of container could be used or could (TE)NORM be used in a different, more useful, way?

Task 3.3.3: Closure of GDF – Priority 3

Undisturbed rock salt is essentially impermeable and therefore salt caverns in salt domes are used for the industrial large-scale storage of liquid and gas products. For example, salt caverns in the Netherlands are used for the storage of gas ('Zoutwending'), gasoil ('De Marssteden') and nitrogen ('Heiligerlee'). Being essentially impermeable, the migration paths for radionuclides are not through the undisturbed rock salt, but rather through the underground tunnels, galleries and the access shafts and the excavation damage zone (EDZ). The latter is an inevitable feature close to the excavated area that is a result of excavation. Although the open spaces will be backfilled, both the backfill and the EDZ will have a permeability after closure of the GDF that will decrease through time due to salt creep and compaction of the backfill.

Brine is the primary transport vector for radionuclides and thus no, or at best minute, amounts of brine should come into contact with the emplaced waste canisters. To avoid brine contact with canisters, engineered barriers that are hydraulically (nearly) impermeable are envisioned in the shafts and in the access drifts between infrastructure area and the emplacement areas.

In Germany, significant and relevant information is available concerning the design and performance of gallery seals (drift seals, dams) in salt-based repositories (for a summary see Buchholz et al., 2020). In addition, the costs for closure make up only a relatively small portion (about 17 %) of the total cost. Therefore, COVRA funding or co-funding of investigations in the closure of the GDF in rock salt is the next 5 till 10 years is not foreseen. However, any opportunity to actively participate in (international) research initiatives to keep up with the knowledge and safety aspects of seals, dams and plugs will be considered.

5.2 Work package 4: Host rock

5.3 Work package 4A: Poorly indurated clays

The host rock forms the main barrier in disposal concepts for both clay and rock salt. Improving knowledge on how it performs 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 and rock salt.

Task 4A.1: Geotechnical properties - Priority 1

The cost estimate of the GDF in OPERA (2011-2017) has been based on the ONDRAF/NIRAS costing approach. The costs for the concrete liner in the GDF can be 70% of the total costs of constructing, operating and closing the GDF. The construction of the shafts and ramp made up a quarter of the design and construct costs in the latest cost estimate and the disposal volume about 3 quarters. Observation and closure have been estimated to be 5%.
The concrete thickness of the liner is in OPERA (2011-2017) based on the Boom Clay properties in Belgium due to lack of available data in the Netherlands. The geotechnical properties of fresh Belgian Boom Clay at 225 metre depth were used. The Boom Clay in the Netherlands is expected to be at least as saline as seawater at suitable disposal depth and the Westerschelde tunnel has a concrete liner support in such Boom Clay. This Boom Clay has been characterised as stiff. The suitable disposal depths in Netherlands may be larger than in Belgium e.g. 500 metre depth is investigated in CORA and OPERA (2011-2017). Consequently, the expected confining pressure is larger and that has an impact on the stiffness of clay. The necessary thickness of the concrete liner depends on the stiffness of clay more specifically: the construction of the GDF is sensitive to the in-situ pressure, cohesion and friction angle (P. Arnold, P. Vardon, et al. 2015); (Arnold, Vardon and Hicks 2015)

What is the nature and variability of poorly indurated clay properties in the Netherlands? Does it depend on the salt content of the clay pore water? What is the in-situ pressure of poorly indurated clay at suitable disposal depth in the Netherlands?

These geotechnical properties need to be experimentally determined from fresh clay cores that have been sampled from relevant Dutch disposal depths. COVRA participates in drilling projects that have been initiated for reasons other than geological disposal of waste since no dedicated drilling programme is foreseen in the next decades. COVRA will fund a part of the drilling costs for the 'Delft Aardwarmte Project' (DAP) if suitable fresh cores of poorly indurated clay can be taken during the making of geothermal wells. The deep geothermal well (DAPWELL) is an EPOS-NL facility. EPOS-NL is the Dutch National Research Infrastructure (NRI) and financed by the Netherlands Organisation for Scientific Research (NWO). In that case, the main part of COVRA funding will be for the experimental research on the investigation of geotechnical properties performed by Delft University of Technology.
Reliable in-situ permeability measurements have so far not been possible in clay for geological disposal purposes due to the disturbance made by coring and the necessary period to recover. The measured in-situ pore water pressure may indicate whether there is a pressure anomaly and to what extent. A larger anomaly will indicate a smaller permeability and is therefore important knowledge for the long-term safety. The participation of COVRA in DAPWELL also allows access to boreholes in which reliable in-situ pore water pressures can be measured in poorly indurated clays at suitable disposal depth.

Task 4A.2: Diffusion-dominated transport - Priority 1

Because of the low permeability of clays, water movements are slow, and transport of radionuclides is expected to take place predominantly by diffusion. There is however yet insufficient evidence for assuming diffusion dominated transport for poorly indurated clay in the Netherlands. One of the easiest elements to assess diffusion within clay is chlorine (Mazurek et al. 2011).
With the available knowledge, poorly indurated clays at disposal depth such as Boom Clay are expected to be present in confined saline aquifers (Griffioen 2015, Griffioen, Verweij and Stuurman 2016) which may make the assessment of diffusion by chlorine difficult. A poorly indurated clay layer separates fresh water from brackish water in the envisaged DAPWELL project. Predictions of chemical measured profiles may provide evidence when diffusion in poorly indurated clay in the Netherlands is allowed to be assumed for geological disposal.

Task 4A.2.1: Gas - Priority 1

In some cases, diffusion for the transport of radionuclides in a clay host rock may no longer be assumed when the gas generated by corrosion of metals in the waste and waste package cannot sufficiently be dissipated by diffusion. COVRA already defined the indicator to assess when diffusion can no longer be assumed in poorly indurated clay in the Netherlands and uses this indicator for its design for HLW disposal package. This indicator is assessed in the currently running EURAD Work Package GAS by the diffusion experiments performed by British Geological Survey on cores conditioned at suitable disposal depth; also cores taken in the Dutch underground similar to those that have been investigated in OPERA (Behrends, Van der Veen, et al. 2016).

The gas generation rate of some waste forms will inevitably be high enough to cause advective migration of potential radionuclides. BGS performs also experiments at these conditions and Delft University of Technology models the data to provide further understanding of the potential preferential gas flow paths. COVRA co-funds the contribution by Delft University of Technology. Co-funding for the contribution by BGS is performed mainly by the English and Belgian WMOs, COVRA co-funds a small fraction of the necessary budget for BGS participation in the EURAD Work Package GAS.

Task 4A.3: Retardation - Priority 2

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. The pore water chemistry determines the speciation of the radionuclides. Representative measurements of the pore water chemistry of poorly indurated clay can only be made on non-oxidised and mechanically undisturbed cores. In OPERA, only fresh cores at unsuitable depth were available but much has been learned how to measure the pore water chemistry (Behrends, van der Veen, et al. 2015, Behrends, Van der Veen, et al. 2016). The understanding of sorption of redox sensitive elements has been increased (Hoving, Sander, et al. 2017, A. Hoving 2018, Hoving, Munch, et al. 2019). The Dutch Geological Survey TNO participates in the currently running EURAD Work Package Fundamental on understanding of radionuclide retention (FUTuRE) in order to increase the understanding of the retention mechanisms of redox sensitive elements e.g. U, Pu, Tc, Np and Se in iron bearing minerals. COVRA co-funds TNO's contribution.

Other experimental data that has been generated within OPERA on Boom Clay (Koenen and Griffioen 2014, Koenen and Griffioen 2016) will also be carefully looked at in order to answer the following question:

What is the speciation of naturally radionuclides and chemical analogues within poorly indurated clay at suitable disposal depth?

Additional funding by COVRA for answering this question is currently limited.

5.4 Work package 4B: Rock salt

Rock salt has many positive properties that make it an attractive medium for the disposal of radioactive waste. Undisturbed rock salt is, for example, essentially impermeable. Furthermore, rock salt will creep and slowly surround other materials forming a tight geologic barrier around the waste. Moreover, there is hundreds of years of experience in salt mining and there is already a licensed and operational GDF (WIPP facility, USA) within rock salt.
Although undisturbed rock salt is essentially impermeable, backfilled (granular salt) access shafts, tunnels and galleries and EDZ will initially have a permeability that could act as a release pathway for radionuclides if a transport medium (e.g. brine) is available.
As the main safety objective of the rock salt is to contain radionuclides, it is essential to understand and to be able to correctly model the long-term convergence and sealing behaviour of shafts, galleries and boreholes created in the construction of the facility, the presence of a potential transport medium (brine) and the solubility of radionuclides in a high saline (brine) environment.
It is also necessary to show that other natural processes like diapirism and subrosion do not adversely affect the safety objective of the rock salt.

Task 4B.1: Geotechnical properties - Priority 1

Numerical models will play a key role in demonstrating the safety of a GDF in rock salt and specifically its long-term safety. They do, however, require extensive knowledge of the Thermal, Hydrological and Mechanical (THM) properties of salt on both short and long term. There is already a wealth of data available on the THM properties of different types of salt (e.g. rock salt, gypsum, sylvite) in (peer-reviewed) journals and reports. In the past, this data has been collected from varied sources and stored in a single database. In the framework of the VIRTUS project, for example, data acquired during more than 30 years of repository research in salt has been collected, evaluated and stored in a single database (Wieczorek, et al. 2013).

However, there is currently no database with THM properties of (rock) salt that is publicly available, easily accessible and actively maintained. Following the example of the Clay Club Catalogue of Characteristics of Argillaceous Rocks and the recommendations made in the Initial Safety Case (Verhoef et al. 2017), a web-based publicly available salt catalogue with properties relevant for a GDF in rock salt should be established.

The salt catalogue will provide a structured way to store key characteristics of (rock) salt for the long term and will help in understanding the differences and commonalities between and within a geological formation. Furthermore, it provides a bandwidth (upper and lower limit) for the different material properties of (rock) salt that are essential to demonstrate the robustness of numerical models and hence the long-term safety of a GDF. Also, by collecting data and combining them, uncertainties of the underground will decrease, potentially reducing the cost of a GDF. The basis for this new database will be the Zechstein cores that are currently stored by TNO. In addition to these cores, additional data from other rock salt formations (for instance the Röt formation) from both the Netherlands and abroad should be added. This also includes other types of salts (e.g. anhydrite) that are likely to be encountered during the constructing of a GDF in rock salt.

Note that this task has not a specific end date, as data will be continued to be collected and added to the database after the end of this task. Furthermore, the database must be flexible and expandable, if needed, to a THMC database (i.e. a database with Thermal, Hydrologic, Mechanical, and Chemical properties).

Setting up a (rock) salt THM database. The focus will be on rock salt of the Zechstein formation, but other types of salts and formations can also be included.

Task 4B.2: Evolution of the permeability-porosity in rock salt - Priority 1

Transport of radionuclides to the surface requires both a transport medium (Task 4B.2.3: Brine availability – Priority 1 and Task 4B.3: Radionuclide Solubility in Brine – Priority 1) and a pathway. Potential pathways that must be considered include the backfilled openings and the EDZ. It is therefore essential for the long-term safety of a GDF to understand the long-term convergence and sealing behaviour of shafts, galleries, EDZ and boreholes that were created during the construction of a GDF.

A great deal is already known about the mechanical flow, damage and healing/sealing properties of rock salt on timescales that are accessible in the laboratory, i.e. up to a few months or years (Alkan, Cinar and Pusch 2007, Hunsche and Hampel 1999, Langer 1999, Lux, et al. 2000, Munson and Dawson 1979, Senseny, et al. 1992, Silberschmidt and Silberschmidt 2000). Much is also known about the compaction and transport properties of granular salt backfill materials on laboratory timescales (Liedtke and Bleich 1985, Spiers, et al. 1990). Extrapolation of such empirical data over tens or a few hundred years is reasonable. However, quantitative physically (mechanistically) based descriptions of these properties that can be applied in numerical modelling of a sealed repository, with convincing uncertainty limits on timescales of 10^3 to 10^6 years, are still largely lacking. In particular, while salt flow and microcrack damage evolution are well understood and well quantified under short-term conditions (Alkan, Cinar and Pusch 2007, Carter, et al. 1993, U. Hunsche 1998, Hunsche and Hampel 1999, Peach and Spiers 1996, Ter Heege, De Bresser and Spiers 2005), diffusive mass transport phenomena - which are known to dominate final densification, healing and sealing of damaged and crushed salt in the long term (Houben, ten Hove and Peach 2013, Spiers, et al. 1990, Urai, Spiers, et al. 1986, Urai, Schléder and Spiers 2008) - are still not. Thus, uncertainties in the timescale on which pores and cracks can remain open and connected in both backfill and EDZ material can be several orders of magnitude (Houben, ten Hove and Peach 2013, Koelemeijer, Peach and Spiers 2012). A better understanding is required for the long-term safety of the GDF in rock salt. This is essential to investigate at an early stage of the long-term research programme.

To address this shortcoming in knowledge, also pointed out in OPERA (Hart et al. 2015), combined experimental and microphysical modelling work is needed to provide a theoretical basis. This should be in the form of constitutive equations, allowing extrapolation of experimental data on the creep and healing/sealing behaviour of EDZ and the backfill to timescales up to about 10^3 or 10^6 years. These constitutive models must describe the creep and porosity/permeability evolution under in-situ conditions on long timescales (Urai et al., 2008), and should be calibrated against lab experiments that are designed to activate these processes. The results of this task will be used in the safety assessment and will determine how long the self-shielding "super" container (cf. Task 3.3.1: Waste package for HLW - Priority 2) should be able to provide full containment.

What is the long-term evolution (10^3-10^6 years) of the permeability-porosity of rock salt (backfill and EDZ) under in-situ conditions?

Task 4B.2.1: Gas Production - Priority 2

Gas in a GDF in rock salt can result from different processes. Gas pockets in rock salt could, for example, migrate towards the GDF. Hydrogen gas could form due to anaerobic corrosion of steel containers and other materials used, and gas generation could result from degradation of organic material.

The build-up of gas has different potentially advert effects on the GDF. The build-up of gas could inhibit convergence of galleries and other open areas in the GDF as it could act as a counter pressure delaying or even halting the natural salt convergence. Gas pressure could also prevent the consolidation of crushed rock salt when used as a backfill and could affect the healing of the excavation damage zone (EDZ); in the EDZ there will be a competition between the increased gas pressure and the resulting pressure-induced microcrack and the healing due to the creep of salt. Thus, if the build-up of gas is significant, it could adversely affect the long-term evolution of the permeability-porosity of rock salt.

Past investigations have indicated that the uncertainties related to gas production and transport are still significant. It was therefore recommended in OPERA (Hart et al. 2015) to address this aspect further in a future programme by assessing the complex behaviour of gas-related processes in safety analyses, such as the pressure build-up of hydrogen gas due to anaerobic corrosion of steel container materials, microbial gas generation from degradation of organic material, and the modelling of gas production in computer codes. Better constraints on the amount of gas production, taking the new repository concept (with and without self-shielding overpack) and expected waste inventory for disposal into account, will improve the performance assessment and could be used for input in other tasks and will eventually determine whether Gas-Salt interaction task will be necessary.

How much gas is produced and how will (through time) gas pressure build up in the repository after closure based on the new repository concept including the overpacks?

Task 4B.2.2: Gas-Rock Salt interaction - Priority 3

During the operational phase of the GDF, gas can escape to the surface via (ventilation) shafts. After the closure of a GDF, gas pressure can start to build up within the GDF. Concurrently, salt creep starts to compact the granular salt backfill used in shafts, galleries and other open spaces. When the generation of gas is limited, as determined in Task 4B.2: Evolution of the permeability-porosity in rock salt – Priority 1, the backfill will eventually become effectively impermeable. If, however, significant gas generation does occur in a repository, its build-up might inhibit convergence of galleries and other open areas within the GDF as it could act as counter pressure. This would delay, or even halt, the natural salt convergence, which potentially prevents the consolidation of the backfill due to a competition between the increased gas pressure and the resulting pressure-induced microcrack on the one hand, and the healing of rock salt on the other hand. For the long-term safety of the repository, it is therefore important to expand the creep and porosity/permeability versus time "laws", as established in Task 4B.2: Evolution of the permeability-porosity in rock salt - Priority 1, to include the gas - rock salt interaction. Thus, how does the gas pressure build up affect the creep and healing of the rock salt in the long term and in turn the GDF?

To address this, both experimental and microphysical modelling work is needed to provide a theoretical basis for this interaction (constitutive equations) and to allow extrapolation of experimental data for the long term. This task will contribute to the performance assessment. However, before this task can be started, better constrains on the amount of gas generated over time is needed to determine whether enough gas is generated to have an influence on the long-term evolution of permeability and porosity.

How does the build-up of gas pressure affect the long-term evolution of permeability and porosity of rock salt and how does it, in turn, affect the closure of the GDF?

Task 4B.2.3: Brine availability - Priority 1

In addition to a pathway (cf. Task 4B.2: Evolution of the permeability-porosity in rock salt – Priority 1), the migration of radionuclides requires a transport medium. In rock salt, an important transport medium is brine. Brine in rock salt can occur in three different locations within rock salt. Brine can be located within a salt crystal (intragranular brine), between salt crystals (Intergranular brine) and as water or hydration bound to hydrous minerals.

The availability of brine is important to the safety case, because (1) it is the primary off-site radionuclide transport medium, (2) it could lead to corrosion of metallic and glass waste forms and waste packages, (3) chloride in brine can reduce criticality concerns, and (4) brine can provide back-pressure to resist long-term creep closure of the repository.

The availability of brine depends on both the properties of the pore fluid (distribution of brine in the salt formation) and the properties of the EDZ – more specifically the distribution and evolution of the EDZ around the access drift and test boreholes. To better understand the availability of brine, experiments are performed in the WIPP facility, New Mexico (USA) by the Department of Energy (DOE). In this experiment, two parallel tests are being conducted in horizontal boreholes. One of the boreholes will be heated while the other will remain unheated. During these experiments, data is collected to (1) confirm the strengths and types of coupled processes (i.e., thermal, hydrologic, mechanical, and chemical - THMC) that govern preferential brine flow paths and canister corrosion, (2) experimentally (lab and field) characterise salt/cement seal interactions, and (3) develop and validate numerical and constitutive models. These experiments, called the heated Brine Availability Test in Salt (BATS), are part of DECOVALEX (DEvelopment of COupled models and their VALidation against EXperiments) and will contribute to the safety assessment in rock salt.

In this work package, COVRA will develop numerical models using COMSOL on the availability of brine and compare these numerical models with the experiments done in the WIPP facility. As these numerical models describe the processes governing the brine

This task will be done in cooperation with Sandia National lab (USA) and BGR/GRS (Germany).

What is the availability of brine in a rock salt repository, which processes influence this availability, and can a numerical model be developed to predict the brine availability?

Task 4B.3: Radionuclide Solubility in Brine - Priority 1

Creep driven convergence will result in the closure of the backfilled open spaces and the EDZ. It might, however, take several hundreds and possible thousands of years before it has reached a negligible permeability. Up to that moment pathways to the surface for radionuclides could exist.

The mobility of radionuclides in the host rock – once a waste container has failed and the waste matrix is in direct contact with brine – depends mainly on the solubility and sorption of the waste in repository conditions. With rock salt being the host rock, solubility of the waste in very high salinities (brine) is the most relevant process while sorption of radionuclides is assumed to be of lesser relevance. Therefore, other radionuclides can become relevant for the long-term safety compared to a GDF in poorly indurated clay. Thus, key questions are: what is the solubility of waste in a very high salinity environment and, which radionuclides will become relevant for the long-term safety?

This research contributes directly to the safety assessment in which the solubility of radionuclides will result in a better and less conservative safety assessment. Furthermore, knowing which radionuclides are relevant for the safety assessment, further research could more focused.

What is the solubility of waste / radionuclides in a high saline (brine) environment?

Task 4B.4: Geological setting - Priority 1

Task 4B.4.1: Bedded salt of the Röt formation - Priority 1

In the Netherlands, there are numerous salt deposits. From old to young these are the Permian aged Rotliegend group, the Permian aged Zechstein group, the Triassic Röt formation, the Triassic Muschel chalk formation, the Triassic Keuper formation and the Jurassic Weiteveen formation. Research in the past (e.g. Hamstra, 1984), has been mainly focused on salt domes of the Zechstein Group due to their large size and available data. Most of the other salt deposits (Rotliegend group, Muschel kalk formation, Keuper formation, Weiteveen formation) are for various reasons not suitable for the construction of a GDF. The rock salt layer within a formation or group is, for example, too thin (< 100 m) or is located beneath the sea or beneath the Zechtstein group; the latter is in most places a suitable rock salt formation.

Based on limited information available (Geluk 2005, Rijks Geologische Dienst 1988), a possible exception might be the Triassic Röt formation. The geological information on this formation is however limited. For instance, the lateral extent, the continuity and the characteristics of the rock salt in the Triassic Röt formation are still poorly known. Thus, what are the geological general characteristics (e.g. thickness, lithology) of the bedded Röt formation and specifically the rock salt within this formation close to the surface (< 1000 m) based on a combination of boreholes and seismic sections?

The outcome of this task should be a map that provides the depth of this formation, its location, thickness and geological history, and will help to focus the research on suitable rock salt formations (bedded or domal rock salt) in the future (cf. Task 4B.4.2: Understanding past, present and future subrosion rates in the Netherlands – Priority 3).

Mapping and characterising the Röt formation, and more specifically the rock salt within this formation in the Netherlands.

Task 4B.4.2: Understanding past, present and future subrosion rates in the Netherlands - Priority 3

Subrosion refers to the washout/dissolution of salt by groundwater flow. It is primarily determined by the amount of solvent (water) available per unit time, the dissolution rate and the solubility of salt minerals present in the salt formation. Due to subrosion, the salt shield around the emplaced waste will gradually be dissolved and could eventually lead to contact between the contents of the GDF and the groundwater system. Thus, subrosion could result in the destruction of a GDF and the release of its contents into the geosphere.

It is thus an important process to understand for the long-term safety of the GDF. It has been addressed in previous Dutch research programmes. For example, using the thickness of the caprock of the Schoonlo and Pieterburen diapir, the subrosion rate for these diapirs were estimated to be in the order of 0.15 respectively 0.14 mm/year (Rijks Geologische Dienst 1988). Other estimates for the subrosion rate are based on theoretical (numerical) models (Glasbergen 1989). These models predict a subrosion rate between of 1-0.06 mm/year. Although some estimates for the subrosion rate of salt domes in the Netherlands thus exist, they are few and contain a relatively large error.

For the long-term safety of the GDF, a systematic review should be undertaken to better quantify the subrosion rate in the Netherlands. Thus, what have the subrosion rates been in the past, what are they now and what can be said about the future using numerical models?

This research should focus on salt domes that have not been used in the past or are currently used for e.g. salt mining or storage of gas. The research must also consider hydrogeological environments in different periods (e.g. glacial and non-glacial periods) to encompass all climates (glacial-non glacial) expected during the normal evolution scenario.

What have the subrosion rates been in the Netherlands in the past, what are they currently and what subrosion rates can be predicted for the future using numerical models?

Task 4B.4.3: Diapirism rates in the Netherlands (Past-Present-Future) - Priority 3

Diapirism is the process in which a salt dome rises upwards (external uplift) relative to the surface. Currently, the prevailing view is that external uplift is driven by differential loading possibly aided by extensional tectonics and other processes, such as upward buoyancy (Hudec and Jacson 2007). Irrespective of the driving force, if a salt dome rises upward and salt around the GDF is simultaneously dissolve by subrosion (cf. Task 4B.4.2: Understanding past, present and future subrosion rates in the Netherlands – Priority 3), this could lead to contact of the radioactive waste with groundwater and ultimately to indigestion within the biosphere. Even if subrosion occurs so slowly that the salt surrounding the GDF is not dissolved before a salt dome reaches the surface, the remaining salt will be eroded quickly at the surface, resulting in exposure that can not only occur by indigestion but also by direct radiation and inhalation of contaminated dust. For the long-term safety of a GDF it is thus necessary to understand the long-term evolution of a salt dome.

There is, however, limited data available on diapirism in the Netherlands. Therefore, it is necessary to investigate diapirism in the Netherlands further. Thus, what was the rate of diapirism in the past, what is it currently and what can be said about the future using a numerical model, and its (possible) relationship with tectonics? Research should focus on salt domes in the Netherlands that have not been used in the past or are currently used for e.g. salt mining or storage of gas.

What have the diapirism rates been in the Netherlands in the past, what are they currently and what diapirism rates can be predicted for the future?

5.5 Work package 5: Surrounding rock formations

The host rocks salt and clay are surrounded by other rock formations. The main safety function of the surrounding rock formations in any disposal system is isolation. This objective may not be achieved if there are major climate changes such as ice ages. Ice sheets were present in the North of the Netherlands e.g. in the Elsterian and Saalian epochs.

Task 5.1: Impact of tunnel valleys - Priority 3

Retreating ice-sheets may locally deeply erode the surrounding rock formations. The appearance of tunnel valleys has been assigned to imminent glaciohydrological stability in the first research programme OPLA with a maximum in depth of 400 metre (van Dijke and Veldkamp 1996). The envisaged disposal depth for a GDF in domal rock salt has been 800 metre for disposal of vitrified HLW before the first national research programme in order to have at least 200 metre of the GDF being surrounded by rock salt (Hamstra 1976), in the first national research programme (OPLA 1989) and in the second research programme (CORA 2001). Recent investigations with seismics showed the past formation of tunnel valleys to a depth of 600 metre in the Northern part of the Netherlands as shown in Figure 14 (ten Veen 2015).

Disposal of waste in a GDF in the poorly indurated clay formation Rupel or Boom Clay started in the second research programme CORA and a disposal depth of 500 metre was used as point of departure. This point of departure was also used for OPERA. A geographical dependent disposal depth may be appropriate for a GDF in poorly indurated clay since the presence of these clay formations are not limited to the Northern part of the Netherlands.

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. The majority of recent studies suggest that there will be a prolonged warm interglacial period, possibly out to over 100.000 years, unless CO_2 emissions are drastically controlled (Archer 2005). If this is a process that could not affect a GDF until some time after 100.000 years, then the hazard potential of the HLW will already have been markedly reduced and, 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.

What is the radiological consequence of deep glacial erosion?

For the next 5-10 years, no siting is foreseen and although the length of the shafts and ramps needs to be increased at larger depth, so far, the major contribution to the total cost estimate remains the construction of the underground facility.
COVRA's funding to answer this research question is therefore limited in the next 10 years. However, COVRA is following the international developments in future climate forecast as part of IGD-TP's collaboration workshops, to stay up to date with the work done by other WMOs.

Task 5.2: Water transport due to climate change - Unique opportunity

COVRA has been coordinating research in geological disposal of radioactive waste since 2010. In the past 10 years, proposals in the European framework to investigate the impact of ice sheets in which COVRA could participate or support has been limited to one. European funding for investigating the impact of ice ages on the safety of disposal of waste has been limited since only some countries, e.g. the Northern European countries need to include this. COVRA is therefore seeking other initiatives for international collaboration. In 2019, an international initiative was launched by SKB and COVRA could participate with limited financial support. COVRA participates in CatchNet[3], an initiative in which this connection is investigated by modelling and natural analogues.

The load exerted by an ice sheet can be the driving force for enhanced flow of water from beneath the ice sheet to other parts of the Netherlands. The topsoil in areas that are not covered by ice sheets are frozen, except for some small lakes (taliks). These taliks are the preferred sinks of the water that was initially beneath the ice sheet if the topsoil and soil are connected. The migration of released radionuclides is then preferentially to these taliks.
This scenario for the migration of water has not yet been included in a safety assessment for a GDF in the Netherlands.

At what depths in the Netherlands are these connections expected in the next 1 million years?

Task 5.3: Salinity deep underground water model - Priority 3

The National Hydrological Instrument was extended in OPERA (Valstar and Goorden 2016, Valstar and Goorden 2017) in order to calculate potential transport of radionuclides between the host rock and biosphere. The surrounding rock formations for a GDF at suitable disposal depth are expected to be Paleogene aquifer systems that are expected to be saline. The fresh-brackish water interface i.e. 150 mg Cl/l, has been investigated in the past (Dufour 2000) and used in OPERA for the hydrodynamic setting of Boom Clay (Vis and Verweij 2014). The current depth of the brackish-saline water interface has been found to be more than 100 metres in most areas of the Netherlands (Stuurman, et al. 2008) and a more detailing of this interface till 1.000 metres would narrow down the necessary assumptions for the pore water chemistry in the clay host rock and surrounding rock formations.

What is the current depth in the Netherlands of the interface between brackish and saline water i.e. 1.000 mg Cl/l. What is the impact of incorporation of the salinity in the extended model?

The increasing salinity as a function of depth would result in a more stratified migration towards the biosphere than without inclusion of the salinity. The travel times from Boom Clay layer to the biosphere (Valstar and Goorden 2016) would be reduced if salinity was included. COVRA's funding to answer this research question is limited in the next years although it would result in a less conservative radiological exposure since it would not necessarily increase the confidence in the post-closure safety.

5.6 Work package 6: Biosphere

Task 6.1: Radionuclide exposure - Priority 4

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

3. See: www.skb.se/catchnet

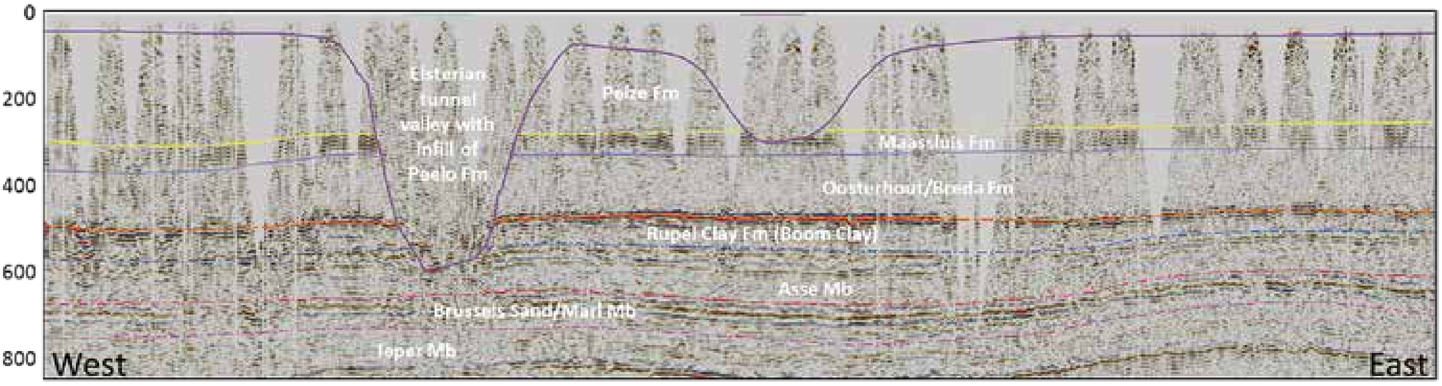


Figure 14: Seismic section in Northern part of the Netherlands (ten Veen 2015)

exposed to radionuclides from the GDF. However, in the timeframe from 10^4 to 10^6 years after closure of the GDF (the period in which radioactivity might reach the biosphere), long-term natural changes in climate will occur and the range of possible biospheres and human behaviour is too wide for reliable modelling. Consequently, for this time period, hypothetical critical groups living in reference biospheres are usually proposed as a basis for modelling potential exposures to radioactivity. The characteristics of these groups and biospheres are chosen to represent circumstances under which the highest doses could arise, given our knowledge of present-day habits and biospheres. Standard practice is to estimate radiation doses to people conservatively, by defining the most highly exposed individual, usually taken to be a member of a subsistence community taking water from a well for drinking and for use by cattle and for crop irrigation, and food from local sources, including rivers or lakes. Information on present day conditions represents the largest and most reliable database for environmental transfer of radionuclides (IAEA 1999) and it is standard practice to use one or more reference biospheres, based on temperate climate conditions (IAEA 2003). The current knowledge is therefore sufficient since the Netherlands is at a conceptual stage. However, it would be interesting to analyse the origin and transport of the naturally occurring radionuclides in drinking water in the Netherlands to enhance the models employed in the safety assessment calculations.

COVRA is interesting in participating in research which tries to answer:

Where do the naturally occurring radionuclides in drinking water come from?

Task 6.2: Chemical toxicity - Priority 4

OPERA and the previous research programmes CORA and OPLA have looked at the impacts only of radioactive elements that might move to 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. This evaluation is expected to be performed when the radiological exposure scenarios have been completed.

In a disposal room within the WIPP facility (USA), an operational geological disposal facility in rock salt, a canister containing waste is loaded onto an emplacement machine that will insert it into a pre-drilled borehole in the wall.
Source: https://wipp.energy.gov/community-relations-photos.asp.

How are we informing stakeholders?

6. Communication and interaction with public participation

6.1 Transparency and publication

For COVRA, transparency about the long-term research programme is very important. Most outputs will be published online. Transparency contributes to a better-informed public and stakeholders, which is essential for societal discussion and open decision-making.

People interested, but not involved in the research programme, will be able to access documentation about the long-term research programme online (including this document). The knowledge generated in the research programme and consolidated into final reports will be published online to foster the dissemination of results. The safety cases, integrating and contextualising all updated knowledge, will be publicly presented and available online.

The Programme Office will encourage researchers to publish their work in scientific journals preferably Open Access as well as in popular scientific magazines. This will allow the non-academic community to freely access the scientific knowledge that has been obtained by the research (co)funded by COVRA

6.2 Communication and outreach

Communication about the research programme is an integral part of the long-term research programme. It constitutes of two forms: communication to stakeholders of the research programme and outreach to the general public about geological disposal of radio-active waste. This is in part sending information, but also requires a dialogue: being responsive to questions and public discussions. These forms of communication supports the technical and societal confidence in disposal and contributes to the national knowledge infrastructure and international network as well as consideration of the multinational track.

COVRA will organise communication and outreach internally and will continue to seek means to make the concept of geological disposal more accessible to the general public. The following means of communication are foreseen during the research programme:

- **Website:** a special section of the COVRA website will be dedicated to geological disposal of radioactive waste and contains accessible information for expert and non-expert public. Through the website contact can be sought with COVRA.
- **News items and/or newsletter:** news items on the website and/or a special/COVRA newsletter to the stakeholders of the research programme update interested readers on the developments of the research programme. These may entail events, outputs, calls for proposals or reports of (international) activities taken place within the long-term research programme.
- **Social media:** news items may also be shared through social media. Social media is more interactive, often more visual, and would allow more direct communication with interested audiences.
- **Public information events:** during each work programme

two public information events (symposia) will be organised to share information about geological disposal of radioactive waste with the general public in an interactive manner. During these events, open for registration to all interested, COVRA (possibly in collaboration with other organisations) organises talks and discussions about the many aspects and issues of geological disposal.
- **Research meetings:** each year researchers involved in the long-term research programme meet to give presentations about their work, to share knowledge and to discuss developments in the Netherlands and abroad.

Other communication activities may be added, for instance incidental invited talks by the programme directors or programme officers at public events or conferences. In addition, COVRA is open to collaboration with museums, archaeologists and students to foster communication and discussion about geological disposal or radioactive waste in accessible and innovative ways.

6.3 Interaction with the public participation activities of the Rathenau Institute and with the ANVS and RIVM

COVRA will organise regular interactions with several independent organisations involved in the national context of disposal of radioactive waste. The goal of these interactions is to exchange knowledge and lessons. The independent position of each organisation is recognised and respected in these interactions. The form of these interactions will be decided during the research programme with the involved organisations. This may for instance result in collaborative annual information meetings. Below we further describe the rationale and context for these interactions with each of the independent organisations.

The Rathenau Institute – a Dutch national institute that performs research related to the societal aspects of science, innovation and new technologies – is tasked by the Ministry of Infrastructure and Water Management with organising a dialogue and performing research on the societal involvement in the decision-making for the final disposal of radioactive waste. In 5 years, this will result in an advice to the state secretary on the decision-making process for the final disposal of radioactive waste. The outcome of both the societal dialogue and the research may influence the long-term research programme, as decisions may change that could influence research needs or timelines.

COVRA finds it important to have an interaction between the public participation and consultation process of the Rathenau Institute and the long-term research programme. The research programme can provide up-to-date facts to the dialogue and the dialogue may result in questions for further research. Therefore, COVRA will organise informal interactions with the Rathenau Institute during the first five years of the research programme. In future work programmes, the results of the Rathenau Institute's activities may lead to further changes to the long-term research programme.

As the national regulator, the ANVS is involved in the preparation of the national policy for geological disposal of radioactive waste (be it in a national or multinational facility) and tasked with supervising the development of a well-developed safety case. The ANVS has therefore to be able to assess the safety assessments and safety cases that COVRA produces without taking part in the research activities themselves. This requires detailed knowledge and understanding of safety cases, safety assessments, their methodology, the research behind them and the processes that lead to their production. To facilitate knowledge transfer and to involve the ANVS, COVRA will organise regular interactions with the ANVS. Other forms of involvement may be considered in the future.

The RIVM is the national TSO of the ANVS. The RIVM provides research and knowledge related to radioactivity, including geological disposal. The RIVM wishes to further build their capacity on radioactive waste disposal to support the ANVS with research and advise. To that end, they can participate in research projects, but they can also benefit from knowledge transfer from the research programme. To that end COVRA will organise regular interactions with the RIVM.

Next to these interactions, COVRA will invite the Rathenau Institute, RIVM and ANVS to the annual research meetings that are organised within the research programme. These research meetings provide a good opportunity to get informed about the ongoing activities within the programme and about the first results or insights obtained. The Rathenau Institute, RIVM and ANVS can attend as audience, but are also invited to present their activities or challenges in the realm of disposal of radioactive waste.

6.4 Work package 7: Communication and education

Informing the general public about the geological disposal of radioactive waste is considered important for the understanding of and support for decision-making on the subject. Communication and dissemination of results is also important for the research community; therefore communication activities will also be directed towards (research and technology) stakeholders. This may strengthen the nuclear knowledge infrastructure in the Netherlands. In that respect, education about geological disposal of radioactive waste and related topics is considered essential to strengthening the nuclear knowledge infrastructure and to ensure sufficient knowledge about the physical, chemical and geological aspects related to the final disposal of radioactive waste.

The communication and dissemination of results of the long-term research programme and the education of students on related subjects are an integral part of the long-term research programme, and therefore covered in this work package.

Task 7.1: Research meetings and public information events

During the long-term research programme meetings with involved researchers and events with the general public are foreseen. Both are intended for information and knowledge sharing, but with a different specific aim:
- The specific aims of the **researcher meetings** are to strengthen the research within the programme and to build a community. These meetings are organised annually and can only be attended on invitation (which may be requested). These meetings of one day or less are organised by the Programme Office and are by default hosted at COVRA in Zeeland.
- The specific aim of the **public information events** is to inform the interested general public with up-to-date information that is grounded in research in order to contribute to a better societal discussion. During each work programme two public

information events are foreseen, which are open to all interested after prior registration. These meetings of one day or less are organised with involvement of the Programme Office and are by default hosted externally at a central location in the Netherlands.

Task 7.2: Knowledge transfer to students

To strengthen the Dutch nuclear knowledge infrastructure, it is important that students are educated in areas and specialisations that are relevant to the nuclear sector in the Netherlands.
For COVRA, and the geological disposal of radioactive waste, the knowledge transfer to students is an integral part of the research programme. Especially the fields of (applied) physics, (applied) chemistry, nuclear science and engineering, geology and (applied) earth sciences at academic level in the Netherlands are targeted for this knowledge transfer. Special collaboration is sought with the University College Roosevelt that is located near COVRA in Middelburg.

In this task a small budget and time is reserved for knowledge transfer to students, which could include the following options:

- **Guest lectures:** lectures on geological disposal of radioactive waste or related subjects by the programme director, programme officers or external researchers involved in the long-term research programme. This may include visits to COVRA or even a course related to radioactive waste management.
- **Internships:** internships of students at COVRA or at projects of the long-term research programme (co)funded by COVRA. In the internship students perform research on an aspect of geological disposal of radioactive waste with guidance/supervision from a professional. An internship is generally between 3-6 months and concerns research at a professional organisation other than a university.
- **Theses:** a thesis is an individual research project intended to obtain a bachelor or master degree. COVRA can raise/sponsor research topics or questions for students to work on during their theses with academic supervision of one of the universities involved in the research programme.
  The duration of these projects is 3-6 months for a bachelor thesis and 6-12 months for a master thesis.
- **Student projects:** specific student projects may be sponsored if they are relevant to the geological disposal of radioactive waste. Sponsoring may be in-kind (people, knowledge, equipment or material) or in-cash (to cover costs).
- **Scholarships:** as part of the research programme COVRA could provide a scholarship (max. €5k) to excellent students if they decide to choose a master specialisation relevant for the geological disposal of radioactive waste and perform their master thesis on a subject on the work programme of the long-term research programme.
- **Student conferences and symposia:** COVRA may sponsor and/or deliver speakers to student conferences and symposia if the subject is related to geological disposal of radioactive waste. This could include a site visit and tour at COVRA.
- **Part-time professorships or industry professors**:
  COVRA may co-fund the installation of a part-time professor (e.g. from industry or WMOs) at a Dutch university if his/her activities in research and/or lecturing are of great added benefit to research on geological disposal of radioactive waste.

COVRA may define activities for knowledge transfer to students, but is also open to receive ideas from interested students. To that end, COVRA will explicitly invite students on its website to express their interest or ideas for internships (at COVRA), theses or student projects on geological disposal of radioactive waste or to request sponsoring for student conferences and symposia.

Task 7.3: Communication channels for the general public

Information on geological disposal of radioactive waste and on the ongoing research programme will be published on a special website that is linked to the website of COVRA. This website should be easy to find and accessible through www.covra.nl. Via the website visitors can contact COVRA.

The website will act as a relevant source of information, containing news items and all consolidated and final documents that can be publicly shared. As the content of these documents are very detailed and complex, the website will provide up-to-date information on geological disposal of radioactive waste that is understandable for an uninformed or non-expert public. Each document that can be downloaded should have a short text (2-3 lines) describing what the document is about, who produced it and when.

Furthermore, the website should provide a link to the public participation activity of the Rathenau Institute. In addition, the website will acknowledge that there is public debate about geological disposal, on which opinions can be found elsewhere (such as on the websites of LAKA and WISE), but only factual materials (based on research in the long-term research programme) can be found on COVRA's website.

In addition, the website will acknowledge that there is public debate about geological disposal, on which opinions can be found elsewhere (such as on the websites of LAKA and WISE), but only materials based on research in the long-term research programme can be found on COVRA's website.

Task 7.4: Collaboration with museums and archaeologists

In the research programme a small budget is reserved for small-scale collaboration with museums and archaeologists. These collaborations are in part intended for communication, knowledge transfer and education, but also for the acquisition of new knowledge. A priori, no specific projects are foreseen, but the budget for this task can be allocated to activities such as:

- Museums visualising and explaining the context of geological disposal of radioactive waste in order to better inform, to foster discussion and to create a better understanding of the challenge with the general public in Zeeland or the Netherlands. Exchange of knowledge or cooperation in research on the transience, degradation and conservation of matter/objects.
- Collaboration with archaeologists to collect relevant information for the safety case e.g. engineered barrier system.

Drilling maschine used to construct underground rock characterisation facility ONKALO® in Olkiluoto crystalline bedrock. Source: Posiva Oy.

7. Budget and allocation of resources and time

7.1 How the research programme is funded

The research programme is funded by COVRA with co-funding from participation in international programmes. The research programme is paid from the COVRA budget. According to the polluter pays principle organisations who deliver their radioactive waste to COVRA pay for all costs. Through this mechanism all waste producers in the Netherlands financially contribute to the long-term research programme. In the future, COVRA may add a specific provision for research on top the waste fees.
This guarantees a steady funding mechanism that is suitable for a long-term research programme.

During the research programme COVRA will be open to partnering with public or private partners when this is in the interest of all partners (including COVRA) and is in line with the goals of the research programme. Partnering may include the co-funding of specific research projects that are in the interest of COVRA and the partner and that is not yet included in the work programme.

The budget for the long-term research programme is determined per five-year work programme and may change over time. For the first work programme (2020-2025) COVRA has secured a budget of 3.5 million euros at the start of the programme. This budget may be extended with internal funding (subject to waste fees) or external (co-)funding during the programme – where we see external (co-)funding opportunities we have indicated this in the task descriptions (Chapters 4 and 5) and in Table 4 (on pages 50 - 52).

7.2 Annual budget for the research programme

The research programme will have an annual cash budget of 700 k€ (2019), as allocated in the COVRA budget. This cash budget may change, depending on the future structure of the waste fees. Additional budget is obtained from co-funding through international projects and partnerships: this may be both in-cash and in-kind.

Apart from the cash budget, COVRA has also 3 FTE available for the research programme. At COVRA's Research, Development & Communication department four people are involved in the research programme for a formation of 3 FTE: the deputy director of COVRA and three researchers. Together they form the Programme Office. The researchers are involved in the coordination of the research programme and its projects/tasks, international collaboration, synthesis of research results and their integration into a safety case. The deputy director of COVRA serves as the Programme Director.

7.3 Allocation of resources for the programme for 2020-2025

The tasks described in this programme are prioritised over time. The available annual budget for 2020-2025 at the start of the programme (2019) is allocated to the tasks that have been given the highest priority in the short-term. During the period 2020-2025 focus will be put on these tasks with Priority 1 and 2 or that are considered a unique opportunity (UO). These tasks will be performed by external research and technology organisations or will be performed in international collaboration. When additional budget is available – for instance through industrial co-funding of specific projects – tasks with lower priority may be performed as well. For some tasks no in-cash budget is available, but an in-kind budget (3 FTE): these tasks are then performed by COVRA.

In the following table we provide for each task an overview of its priority, whether funding is allocated to the task, whether the task is executed by COVRA or externals or in international collaboration and whether COVRA is open and sees opportunities for project-specific co-funding by industry.

Table 4: Characteristics of work packages and tasks in terms of priority, funding, execution and collaboration

Work packages and tasks	Priority for 2020-2025 (1 = high, 4 = low, UO = unique opportunity)	COVRA funding allocated for 2 020-2025	Done by COVRA or externals	Inter-national collaboration	Option for industry or partners to co-fund
WP0: Programme management and coordination					
Task 0.1: Programme management and monitoring		▪	COVRA		
Task 0.2: International collaboration and networking		▪	COVRA	▪	
Task 0.3: Programme development for continuity		▪	COVRA & IAB		
Task 0.4: Expert advice to the programme director and programme office		▪	COVRA & Externals	▪	
WP1: Programme strategy					
T1.1: Overview of alternatives for national geological disposal facilities	1	▪	COVRA		
T1.2: Routes to multinational GDF implementation	UO	▪	COVRA & Externals	▪ ROUTES	
T1.3: Synthesis of knowledge on improving cost estimates and cost optimisation	UO	▪	COVRA & Externals	▪ ERDO	
T1.4: Common approach to acceptance to a disposal facility	UO	▪	COVRA & Externals	▪ ERDO / ROUTES	
T1.4.1: Common approach to disposability assessment	4		COVRA & Externals	▪ ROUTES	▪
T1.5: Deep Borehole Disposal	UO	▪	COVRA & Externals	▪ ERDO	
T1.6: Reversibility/retrievability	3	▪	COVRA		
T1.7: Disposal concept and cost estimate for a GDF in rock salt	1	▪	COVRA & Externals		
T1.7.1: Cost estimate for a GDF in rock salt	1	▪	COVRA & Externals		
T1.7.2: Review of different disposal concepts in rock salt	1	▪	COVRA & Externals		
WP2: Safety case and integration					
T2.1: Safety case development for a GDF in rock salt	1	▪	COVRA		

T2.2: Integration of knowledge on rock salt	1	▪	COVRA		
T2.2.1: Development/improvement of numerical methods & tools for modelling coupled processes	UO	▪	COVRA & Externals	▪ EURAD	
T2.2.2: Methodological approaches to uncertainty and sensitivity analysis	UO	▪	COVRA & Externals	▪ EURAD	
T2.2.3: Uncertainties related to human aspects	UO	▪	COVRA & Externals	▪ EURAD	
T2.3: Safety case development for a GDF in poorly indurated clays	1	▪	COVRA		
T2.4: Integration of knowledge on poorly indurated clays	1	▪	COVRA		
WP3: Engineered barrier system					
T3.1: Spent research reactor fuel	2*		Externals & COVRA		▪
T3.2: EBS for poorly indurated clay	2 & 4	▪	COVRA	▪ EURAD	▪
T3.2.1: Waste package for HLW	2*	▪	Externals & COVRA		▪
T3.2.2: Vitrified HLW	2	▪	COVRA	▪ EURAD	
T3.2.3: Waste package for LILW	2	▪	COVRA	▪ EURAD	
T3.2.4: Closure of GDF	4		COVRA		
T3.3: EBS for rock salt	2	▪	COVRA & Externals		
T3.3.1: Waste package for HLW	2	▪	Externals		
T3.3.2: Waste package for (TE) NORM	2*		COVRA & Externals		▪
T3.3.3: Closure of GDF	3		COVRA & Externals		
WP4: Host rock:					
WP4A: Poorly indurated clays					
T4A.1: Geotechnical properties	1		Mainly Externals	▪ DAPWELL	
T4A.2: Diffusion-dominated transport	1		COVRA & Externals	▪ DAPWELL	
T4A.2.1: Gas	1		COVRA & Externals	▪ EURAD	
T4A.3: Retardation	2		Mainly Externals	▪ EURAD	

WP4B: Host rock: Rock salt					
T4B.1: Geotechnical properties	1		Externals		
T4B.2: Evolution of the permeability-porosity in rock salt	1		Externals		
T4B.2.1: Gas production	2		Externals		
T4B.2.2: Gas-Rock Salt interaction	3		Externals		
T4B.2.3: Brine availability	1		COVRA & Externals	▪	
T4B.3: Radionuclide solubility in Brine	1		Externals		
T4B.4: Geological setting	1		COVRA & Externals		
T4B.4.1: Bedded salt of the Röt formation	1		COVRA & Externals		
T4B.4.2: Understanding past, present and future subrosion rates in the Netherlands	3		Externals		
T4B.4.3: Diapirism rates in the Netherlands (Past-Present-Future)	3		Externals		
WP5: Surrounding rock formations					
T5.1: Impact of tunnel valleys	3		Mainly Externals		
T5.2: Water transport due to climate change	UO	▪	Mainly Externals	▪ CatchNet	
T5.3: Salinity deep underground water model	3		Externals		
WP6: Biosphere					
T6.1: Radionuclide exposure	4		Externals		
T6.2: Chemical toxicity	4		Externals		
WP7: Communication and education					
T7.1: Research meetings and public information events		▪	COVRA		
T7.2: Knowledge transfer to students		▪	COVRA		▪
T7.3: Communication channel for the general public		▪	COVRA		
T7.4: Collaboration with museums and archaeologists		▪	COVRA		

* Budget reserved, but requires additional co-funding from industry or international partners

7.4 Planning of activities for the programme for 2020-2025

The first work programme runs from 2020 to 2025. In these five years the funded tasks described in Chapters 4 and 5 will be performed. The planning of these activities is given in the following table. In this table the dark areas indicate the years in which these tasks will be performed. Some tasks are more or less continuous and run over all years of the programme, for instance tasks related to programme management and communication. Other tasks have a priori no funding allocated and are therefore not indicated in the planning – these activities may only be performed during the first work programme when additional budget and time is available. The black square indicates in what year the deliverable of the task should be realised.

A more specific planning and description of deliverables will be developed on task (or project) level. These will be part of the terms of reference for external research organisations. Specific deadlines will be agreed with external research organisations.

Table 5: Planning of work packages and tasks in the first work programme (with priority 1, 2 and UO)

Tasks	2020	2021	2022	2023	2024
WP0: Programme management and coordination					
T0.1: Programme management and monitoring					
T0.2: International collaboration and networking					
T0.3: Programme development for continuity					▪
T0.4: Expert advice to the programme director and programme office					
WP1: Programme strategy					
T1.1: Overview of alternatives for national geological disposal facilities					▪
T1.2: Routes to multinational GDF implementation				▪	
T1.3: Synthesis of knowledge on improving cost estimates and cost optimization					▪
T1.4: Common approach to acceptance to a disposal facility		▪			
T1.4.1: Common approach to disposability assessment					
T1.5: Deep Borehole Disposal		▪			
T1.6: Reversibility/retrievability					
T1.7: Disposal concept and cost estimate for a GDF in rock salt					
T1.7.1: Cost estimate for a GDF in rock salt					▪
T1.7.2: Review of different disposal concepts in rock salt				▪	
WP2: Safety case and integration					
T2.1: Safety case development for a GDF in rock salt					▪
T2.2: Integration of knowledge on rock salt				▪	
T2.2.1: Development/improvement of numerical methods & tools for modelling coupled processes			▪		

T2.2.2: Methodological approaches to uncertainty and sensitivity analysis			▪		
T2.2.3: Uncertainties related to human aspects			▪		
T2.3: Safety case development for a GDF in poorly indurated clays					▪
T2.4: Integration of knowledge on poorly indurated clays				▪	
WP3: Engineered barrier system					
T3.1: Spent research reactor fuel					
T3.2: EBS for poorly indurated clay					
T3.2.1: Waste package for HLW					
T3.2.2: Vitrified HLW					
T3.2.3: Waste package for LILW					
T3.2.4: Closure of GDF					
T3.3: EBS for rock salt					
T3.3.1: Waste package for HLW					
T3.3.2: Waste package for (TE)NORM					
T3.3.3: Closure of GDF					
WP4: Host rock					
WP4A: Poorly indurated clays					
T4A.1: Geotechnical properties					
T4A.2: Diffusion-dominated transport					
T4A.2.1: Gas					
T4A.3: Retardation					
WP4B: Rock salt					
T4B.1: Geotechnical properties					▪
T4B.2: Evolution of the permeability-porosity in rock salt				▪	
T4B.2.1: Gas production				▪	
T4B.2.2: Gas-Rock Salt interaction					
T4B.2.3: Brine availability					▪
T4B.3: Radionuclide solubility in Brine				▪	
T4B.4: Geological setting					

T4B.4.1: Bedded salt of the Röt formation					
T4B.4.2: Understanding past, present and future subrosion rates in the Netherlands					
T4B.4.3: Diapirism rates in the Netherlands (Past-Present-Future)					
WP5: Surrounding rock formations					
T5.1: Impact of tunnel valleys					
T5.2: Water transport due to climate change					
T5.3: Salinity deep underground water model					
WP6: Biosphere					
T6.1: Radionuclide exposure					
T6.2: Chemical toxicity					
WP7: Communication and education					
T7.1: Research meetings and public information events					
T7.2: Knowledge transfer to students					
T7.3: Communication channel for the general public					
T7.4: Collaboration with museums and archaeologists					
Pattern fill indicates that the task is a heading for sub tasks or that the task has a priority of 3 or 4.					

A prototype of a disposal machine in the Äspö Hard Rock Laboratory, Sweden. Source: SKB AB/Curt-Robert Lindqvist.

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Underground tunnels at 450 m level in Äspö Hard Rock laboratory.
Source: SKB AB/Curt-Robert Lindqvist

9. Glossary of abbreviations

(TE)NORM	(Technically Enhanced) Naturally Occurring Radioactive Materials
ACED	Assessment of Chemical Evolution of ILW and HLW Disposal Cells
ANVS	Authority for Nuclear Safety and Radiation Protection
BATS	Brine Availability Test in Salt
BD	Borehole Disposal
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
BGS	British Geological Society
BIOMASS	BIOsphere Modelling and ASSessment
C	Costing driver
Cf.	Confer
COMSOL	Multiphysics simulation software
CORA	Commissie Opberging Radioactief Afval
COVRA	Centrale Organisatie Voor Radioactief Afval
CSD-c	Standard Canister of Compacted Waste
CSD-v	Standard Canister of Vitrified Waste
D	Disposability driver
DAP	Delft Aardwarmte Project
DAPWELL	Delft Aardwarmte Project Geothermal Well
DOE	Department of Energy
DONUT	Development/improvement Of NUmerical methods & Tools for modelling coupled processes
DV-70	Standard waste container for U3O8
EBS	Engineered Barrier System
EC	European Commission
EDZ	Excavation Damage Zone
EPOS-NL	Dutch contribution to the European Plate Observatory System
EPZ	Elektriciteits Produktiemaatschappij Zuid-Nederland
ERDO	European Repository Development Organisation
EU	European Union
EURAD	European Joint Programme on Radioactive Waste Management
Euratom	European Atomic Energy Community
FTE	Full Time Equivalent
FUTuRE	Fundamental understanding of radionuclide retention
GAS	Mechanistic understanding of GAS transport in clay materials
GDF	Geological Disposal Facility
GEOSAF	Demonstrating the Safety of Geological Disposal Project
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit - Global Research for Safety
HADES	Underground laboratory in Boom clay in Belgium
HFR	High Flux Reactor
HLW	High Level Waste
HOR	Hoger Onderwijs Reactor
IAB	International Advisory Board

IAEA	International Atomic Energy Agency
ICK	Interdepartmental Commission on Nuclear Energy
IGD-TP	Implementing Geological Disposal of radioactive waste-Technology Platform
IGSC	Integration Group for the Safety Case
ILW	Intermediate Level Waste
KCB	Kerncentrale Borssele
LAKA	LAndelijk Kernenergie Archief
LILW	Low and Intermediate Level Waste
LWC	Legacy Waste Characterisation
METRO	Modellen voor veiligheid en Economische aspecten van Terughaalbare opberging van hoog-Radioactief afval in de diepe Ondergrond
N.V.	Naamloze Vennootschap
NEA	Nuclear Energy Agency
NGO	Non-Governmental Organisation
NWO	Netherlands Organisation for Scientific Research
NPRA	Nationaal Programma Radioactief Afval
NRG	Nuclear Research Group
OECD	Organisation for Economic Co-operation and Development
ONDRAF-NIRAS	Nationale Instelling voor Radioactief Afval en verrijkte Splijtstoffen Belgium
OPERA	Onderzoeksprogramma Eindberging Radioactief Afval
OPLA	OPberging te LAnd
R&D	Research and Development
RID	Reactor Institute Delft
RIVM	Rijksinstituut voor Volksgezondheid en Milieu
ROUTES	Waste management ROUTES in Europe from cradle to grave
RWM	Radioactive Waste Management
S	Confidence in long-term safety driver
SIMS	Small Inventory Member States
SKB	Swedish Nuclear Fuel and Waste Management Company
SRRF	Spent Research Reactor Fuel
SSD	Small-Scale Disposal
SSK	Standaardsystematiek voor Kostenramingen
T	Task
TDB	Thermodynamic Database Project
THM	Thermal, Hydrologic, Mechanical
THMC	Thermal, Hydrologic, Mechanical and Chemical
TNO	Toegepast Natuurwetenschappelijk Onderzoek
ToR	Terms of Reference
TORAD	Terughaalbaar Opslaan van Radioactief Afval in diepe Boorgaten
TSO	Technology Support Organisation
TU	Technical University
U_3O_8	Triuranium octoxide
UMAN	Uncertainty Management multi-Actor Network
UO	Unique Opportunity
URL	Underground Research Laboratory
USA	United States of America
UU	Utrecht University
vHLW	Vitrified High Level Waste
VIRTUS	Virtual Underground Laboratory in Salt
VROM	Former Dutch Ministry for Spatial Planning and Environment
WAC	Waste Acceptance Criteria
WIPP	Waste Isolation Pilot Plant
WISE	World Information Service on Energy
WMO	Waste Management Organisation
WP	Work Package

COVRA NV

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Spanjeweg 1
4455 TW Nieuwdorp

Postbus 202
4380 AE Vlissingen

E: info@covra.nl
T: +31(0)113 616 666

9 789083 088501 >