R&D on the Feasibility of Operating a Geological Disposal Facility for High-Level and Long-Lived Radioactive Waste in Belgium - Further Development of Operational Concept – 14386

Bernt Haverkamp*, Wolfgang Filbert*, Philipp Herold*, Gerald Nieder-Westermann* and Philippe Van Marcke**
* DBE Technology GmbH, 31201 Peine, Germany
** ONDRAF/NIRAS, 1210 Bruxelles, Belgium

ABSTRACT

ONDRAF/NIRAS, the Belgian Agency for Radioactive Waste and Enriched Fissile Materials, examines geological disposal in poorly indurated clay as the reference solution for the long-term management of its high-level and/or long-lived radioactive waste. ONDRAF/NIRAS is currently preparing a safety and feasibility case (SFC), which will describe, substantiate and, as far as possible, quantify the safety and feasibility of the proposed disposal system.

DBE TECHNOLOGY GmbH supports ONDRAF/NIRAS by executing feasibility studies in regard to the possible future operation of such a repository. The studies concentrate on essential parts of the conceptual repository design that need further development and confirmation that a future implementation of the concept will be feasible, and complying with safety requirements as well as the requirement that costs are to be commensurate with available funding.

The feasibility studies that have been completed to date are mainly concerning the conceptual planning of a hoisting system for payloads of up to 80 tons, the development of an underground transport and waste emplacement system, and the planning of the repository ventilation. All systems for transport and ventilation are based on state-of-the-art equipment or components that have been built and tested in a 1/1 scale during R&D work carried out by DBE in connection with the German repository projects at Gorleben and Konrad.

As result of the analyses conducted as part of the feasibility studies several recommendations for optimizations of the original design basis were formulated, which partly led to significant changes including a recommendation to increase the initially planned cross sectional profiles of the access and disposal drifts. In all cases, however, systems with proven technical feasibility could be designed, which also complied with the requirement for safe and cost effective technical implementation.

INTRODUCTION

ONDRAF/NIRAS, the Belgian Agency for Management of Radioactive Waste and Enriched Fissile Materials, has been studying geological disposal in poorly indurated clay as an option for the long-term management of its high-level (C-Waste) and long-lived low- and intermediate-level radioactive waste (B waste). The clay formations considered are Boom Clay and Ypresian Clays [1].

To this purpose, a safety concept and a design for the disposal facility [2, 3] have been developed. For the potential implementation of the geological disposal system, ONDRAF/NIRAS has chosen a cautious, stepwise process, punctuated by the submission of key documents to the government. These documents that are intended to support decisions by the government are called “safety and feasibility cases”. They mark the end of successive stages in the disposal program.

Currently, ONDRAF/NIRAS is preparing the first Safety and Feasibility Case (SFC-1) for geological disposal. This document will consist of a series of documents integrating all scientific and technological arguments and evidences describing, substantiating and, if possible, quantifying the safety and feasibility of the proposed disposal system at a conceptual design level.

To support the preparation of SFC-1, ONDRAF-NIRAS has launched a R&D feasibility program that is scheduled until the end of 2014 consisting of several studies that aim at confirming that there are no fundamental flaws or showstoppers in the feasibility of building and operating the components and facilities for geological disposal according to the conceptual design. The main topics to be addressed by these studies are:

- the fabrication of the disposal waste packages;
- the underground repository construction;
- the operation of the repository; and
- the closure of the repository.

This paper focusses on the key aspects of the operation and the closure of the planned subsurface facility that are being examined and optimized as part of the feasibility studies being conducted by DBE TECHNOLOGY on behalf of ONDRAF/NIRAS.

BOUNDARY CONDITIONS FOR THE BELGIAN CONCEPT FOR GEOLOGICAL DISPOSAL

The safety concept, describing the components of the complete disposal system and the assigned safety functions is the basis for the subsequently designed disposal facility that has to meet these safety functions. Various boundary conditions have to be considered for the safety concept as well as for the disposal design, in particular, the relevant international and national regulatory framework and some strategic choices made by ONDRAF/NIRAS [2]. These choices are working hypotheses that had to be made in the absence of institutional decisions to manage the development of the geological disposal system in a focused way. The main strategic choices are:

1. The designated host rock formation will be poorly indurated clay (Boom Clay or Ypresian Clays).
2. The materials and implementation procedures will not unduly perturb the safety functions of the host formation or of any other component of the disposal system.
3. In the case of heat-generating waste (i.e. the category C waste), the engineered barriers will be designed to provide complete containment of the wastes and associated contaminants at least during the thermal phase.
4. Waste types will be divided into groups to be disposed of in separate sections of the repository.
5. Repository construction and operation will proceed as soon as possible, but taking due account of scientific, technological, societal and economic considerations.
6. The different disposal galleries and repository sections, and the repository as a whole, will be closed as soon as practically possible following disposal of the wastes.
7. There are preferences for permanent shielding of the wastes and for minimizing all underground operations.
8. There are preferences for materials and implementation procedures for which broad experience and knowledge already exist.
9. Repository planning will assume that post-closure surveillance and monitoring will continue for as long as reasonably possible.

According to the developed disposal concept the waste will be post-conditioned in disposal packages, which are then disposed in an underground repository. Concurrently with the disposal operations, the already filled parts of the repository will be closed by progressively backfilling and by installing seals at several locations within the repository.

REPOSITORY DESCRIPTION

The reference design for a repository as considered in the R&D program on geological disposal consists of a disposal facility constructed at a depth of 230 m in Boom Clay (Fig. 1) [4]. The disposal packages will be transferred to the repository along a large waste shaft separating the repository in a category B and category C waste section (strategic choice n°4). The two outer shafts to be seen in Fig.1 will be smaller and dedicated to the transport of material and personnel and will allow the proper ventilation of the repository. The dead-end disposal galleries will be constructed perpendicular to the access gallery that will connect the two shafts. The decision to use dead-end disposal galleries instead of connected galleries is related to long-term safety considerations, as connected galleries can create a preferential pathway for water circulation which could offer a transport path for radionuclide migration.

The current disposal strategy foresees waste emplacement to be conducted in two phases, separated by several decades. LILW will be emplaced first, followed by emplacement of the HLW. Accordingly, during operation there will be probably only two operating shafts as the outer shaft of the B-waste field is intended to be closed after the end of B-Waste disposal operation.

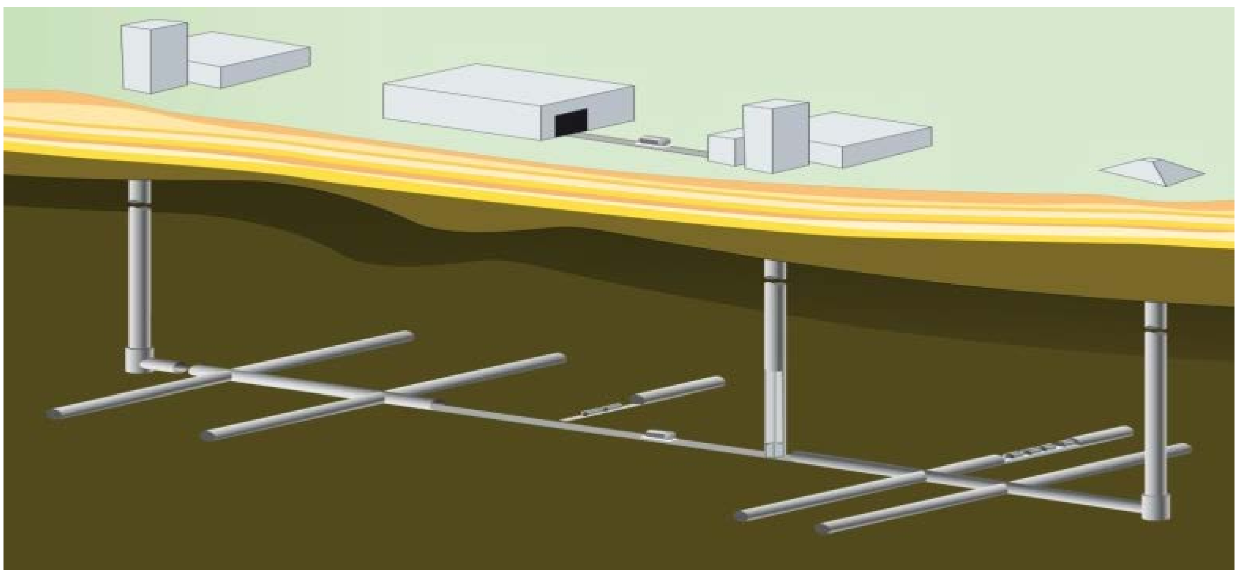

Fig. 1: Layout of the current repository design

Shafts

All transport between surface and the underground repository will be carried out via shafts as connection pathways. The decision in favor of shafts and against ramps as alternative solution was taken mainly due to economic considerations.

In regard to the diameter of the two outer shafts only reduced requirements exist and their construction should not cause significant problems as demonstrated by sinking of the two shafts at Mol for the Underground Research Facility (URF) HADES at a depth of 230 m in Boom Clay. A more challenging task is the planning and construction of the waste shaft. Its diameter is determined by the dimensions of the waste packages and the design of hoisting equipment and shaft installations. Subsequent to initial studies the required open or inner diameter of the shaft was set to 10 m [4]. An inner shaft diameter of 10 m also requires a significant wall or liner thickness. A shaft to be sunk through the overlying rock formations would therefore require an excavation diameter of approximately 12 m (i.e. outer shaft diameter). These diameters are significantly larger than those of either of the two shafts of the HADES facility and range at the limit of existing experience with similar shafts constructed in comparable environments. R&D studies in relation to the waste shaft were therefore aimed at minimizing the inner or open diameter of the shaft by developing a hoisting system optimized in regard to the required space (see below).

Galleries

The internal diameter of the disposal galleries was set at 3 m. Construction of the PRACLAY gallery in HADES (Fig. 2) had shown that using the proposed excavation technique the construction of smaller galleries becomes difficult [5]. However, R&D studies in regard to emplacement operation and waste emplacement indicate that this diameter probably will have to be increased to about 3.5 m, at least for the B-Waste galleries (see below).

Fig. 2: Connecting gallery of the HADES URF with concrete wedge block lining

The minimum diameter of the access galleries is determined by the required space for turning the waste containers at the entrance of the disposal galleries. Considering the maximum length of 6.25 m for the Supercontainer, an internal diameter of 6 to 7 m will be sufficient to carry out the turning operation. The exact diameter will depend mainly on safety requirements by the mining authorities (see below).

The maximum length of the blind disposal galleries was set to 1000 m as longer galleries would become unmanageable and assuring their ventilation would become difficult.

The length of the access galleries is determined by the number of disposal galleries and the spacing between these galleries. A minimum distance between adjacent disposal galleries is necessary to guarantee the stability of the crossing areas and to avoid interference between processes around adjacent galleries (like the evolution of an excavation disturbed zone or the generation of gas). For the heat-emitting waste the distance between adjacent disposal galleries also has to be sufficient to limit the temperature increase in the surrounding clay massif. These requirements led to a minimum spacing of 50 m between the galleries for category B waste and vitrified high-level waste and a minimum spacing of 120 m for spent fuel galleries assuming a spacing of 1 m between adjacent Supercontainers in the disposal galleries [4].

As the Boom Clay has a plastic character and only limited strength underground excavations require a lining. The proposed gallery lining consists of unreinforced concrete wedge blocks and was tested during the construction of the two most recently excavated galleries in the HADES facility [5, 6] (Fig. 2).

REPOSITORY OPERATION

Main operational activity within the repository is the transfer of waste packages from the surface to the underground, their transport from the shaft landing station towards the designated emplacement location and the emplacement of the waste package.

Following regulatory requirements, these activities have to be carried out in a reversible manner, which means that safe retrieval of the waste packages must be possible as long as the respective disposal galleries have not been backfilled and sealed. It is also required that in this case the retrieval operation can be carried out by using the same or similar equipment as used for the emplacement. Accordingly during the development of equipment and procedures for the future operation, this retrieval requirement has to be taken into consideration.

Another important aspect to be considered in regard to the future repository operation is the demonstration that the proposed ventilation system will allow the safe and reliable ventilation of the repository during the different stages of its evolution.

Shaft Transport of the Disposal Packages

With a maximum weight of 69 tons for the Supercontainers and an extra 10 tons for the transport trolley, the maximum payload to be transported through the waste shaft is approximately 80 tons. According to the reversibility requirement the hoisting system must be able to transport this load either upwards or downwards. Although there is widespread experience from the mining industry, State-of-the-art in conventional mines is a maximum payload of approximately 50 tons with upward hoisting direction.

The 80 tons payload in the Belgian disposal concept is significantly greater than currently employed in the mining industry and to date no hoisting systems for such a high payload exist.

However, the hoisting system for a possible future repository in Gorleben is designed for a comparable payload of 85 tons. Feasibility studies including a comprehensive evaluation of potential operational risks for this system were performed and all key components of the hoisting system that were not state-of-the-art at that time were tested on a 1:1 scale. The planned hoisting system was approved by the authorities as suitable for the licensing procedure and can be regarded as proven technology. It was therefore chosen as reference design for the conceptual development of a hoisting system for the Belgian disposal concept.

The proposed multi-cable hoisting system for a total payload of 80 tons has been optimized to accommodate the largest combined dimensions from both B- and C-waste package types. Fig. 3 shows the resulting shaft cross section with its diameter of 7,80 m.

The X-profile guide rail configuration allows the use of a single rail component to guide both, cage and counterweight and thereby requires significantly less space than separate guiding systems or rope guiding that are commonly used in mining.

The design foresees the use of a six-cable Koepe friction winder to move the payload and the hoist cage on the one side and the corresponding counterweight on the other side up and down the shaft.

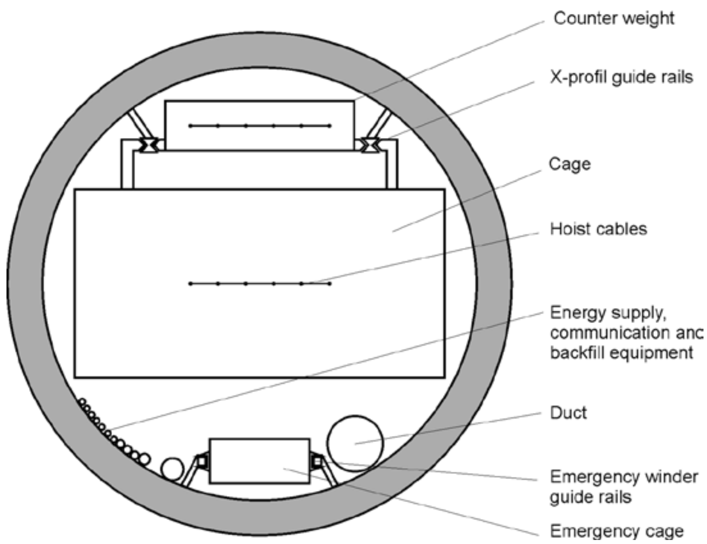

Fig. 3: Shaft cross section of proposed hoisting system

The hoist cage has been specifically designed to meet the requirements associated with the heavy payload. One important feature is a so-called "false bottom", a waste transport platform that is free to move vertically within the cage framework. At the shaft stations cage latches are used to grasp and immobilize this platform. With the false bottom platform immobilized, the stresses on the cables can be equalized prior to loading and unloading operations (Fig. 4).

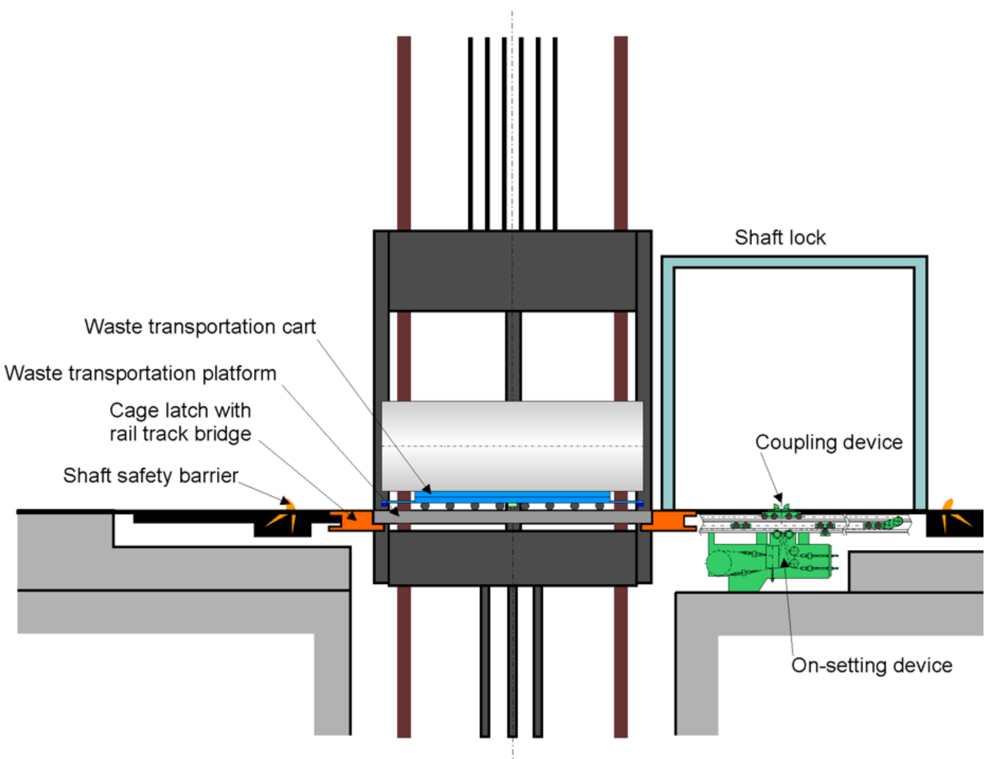

Fig. 4: Configuration of Shaft House Surface Station Safety Systems

Several safety features are included throughout the whole hoisting system design. At the surface shaft station, safety features are included in the design to exclude the possibility of either a waste shipment or locomotive from falling down the shaft by eliminating all direct pathways to the shaft. Underfloor onsetting machines are used at the shaft stations to load and unload the hoist cage, removing the need for a locomotive to approach the shaft. SELDA systems are used in both the headframe and in the shaft sump to avoid overwind accidents. An emergency winder will be available to evacuate personnel from the subsurface facilities if required.

The components of the hoisting system designed for the Belgian disposal concept are derived from available conventional mining technologies or from modified technology that had been confirmed as feasible technology by demonstration testing for the Gorleben hoisting system. The design is feasible and represents the current state-of-the-art in hoisting system design.

Underground Transport and Waste Disposal

For the initial Belgian concept [4] two transport solutions were examined: an air cushion system which was preferred at the time, and an alternate rail-bound system. A State-of-the-Art study regarding the Belgian disposal concept [7], which among other aspects examined air cushion systems and their operational requirements draw attention to significant difficulties associated with implementing an air cushion transport system in the subsurface particularly with respect to requirements for floor evenness and smoothness. Based on these results, ONDRAF/NIRAS asked DBE TECHNOLOGY GmbH to develop an alternative transportation.

The newly proposed system utilizes an optimized hybrid rail-wheel configuration for subsurface transport using a battery driven locomotive. The concept is largely based on the tested and proven underground transport concepts developed for a potential future German repository in a salt dome such as the Gorleben one and on the fully licensed German geological repository being constructed at Konrad for disposal of non-heat generating waste. A manned locomotive similar to that proposed for the implementation in a future Belgian repository has been procured and tested as part of a prototyping effort associated with the Gorleben project (Fig. 5). Alternatively a remotely operated locomotive could likely be designed.

Fig. 5: DBE Transport System with Mining Locomotive and Transport Cart

The main adaptations in regard to the Belgian requirements were: the use of turntables, which in turn has been tested at the Konrad repository and the transportation guiding systems used by both the waste transport cart and the locomotive to avoid the use of rails inside disposal galleries.

The access gallery will be outfitted with a concrete floor to provide a path for the transportation. Grooves in the floor with u-shaped rails, which can be removed during closure operations, will guide the locomotive and the transport trolley through the access gallery. At the crossing with the disposal gallery a removable turning table will be installed. After having turned the disposal package by the turning table, a second locomotive can push the disposal packages into the disposal gallery (Fig. 6). Alternatively an on-setting device similar to that used at the shaft loading stations could be used, in which case no second locomotive would be needed.

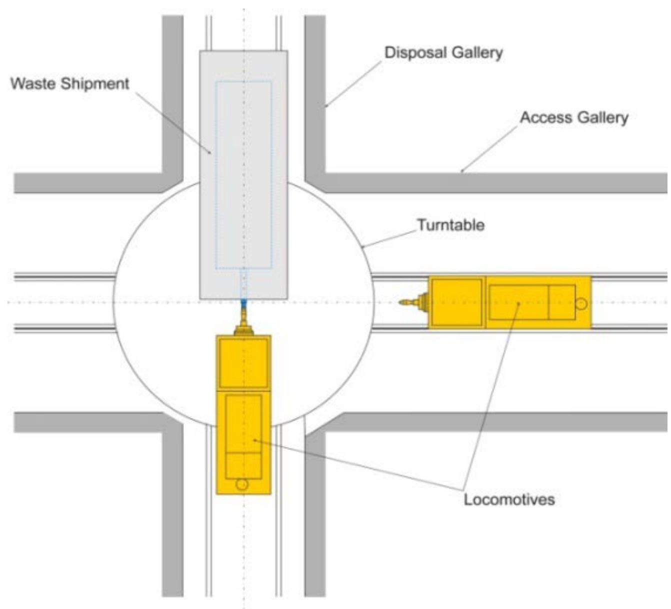

Fig. 6: Turning table at the gallery crossing, a second locomotive pushes the waste trolley along the disposal gallery

The disposal galleries have a concrete floor structure that allows the emplacement of the disposal packages (Fig. 7). The guidance of transport trolley and locomotive is done by the floor sidewalls and rolls attached to the side of trolley and locomotive.

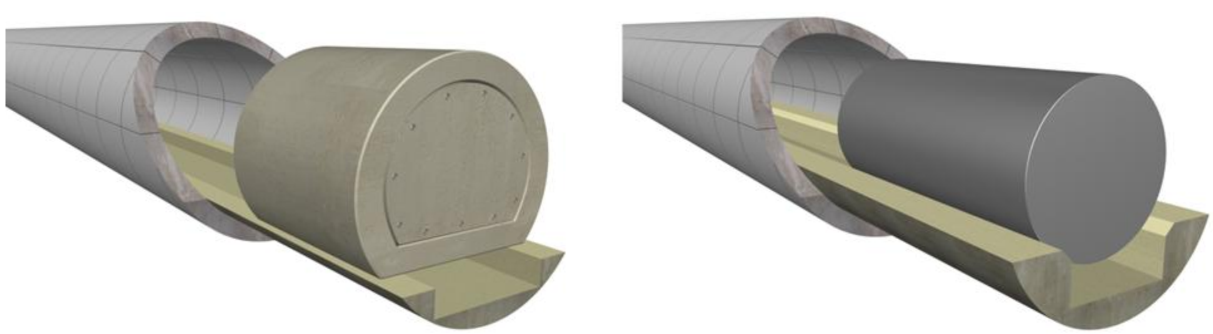

Fig. 7: Monolith and Supercontainer emplaced on the floor structure in the disposal gallery.

The transfer trolley has a hydraulic lift system, which keeps the load floor with the waste package in a raised position during its transport. Once the transport cart arrives at the disposal position, the load floor is lowered so that the disposal package comes to a rest on the floor structure and the cart can be pulled back (Fig. 8).

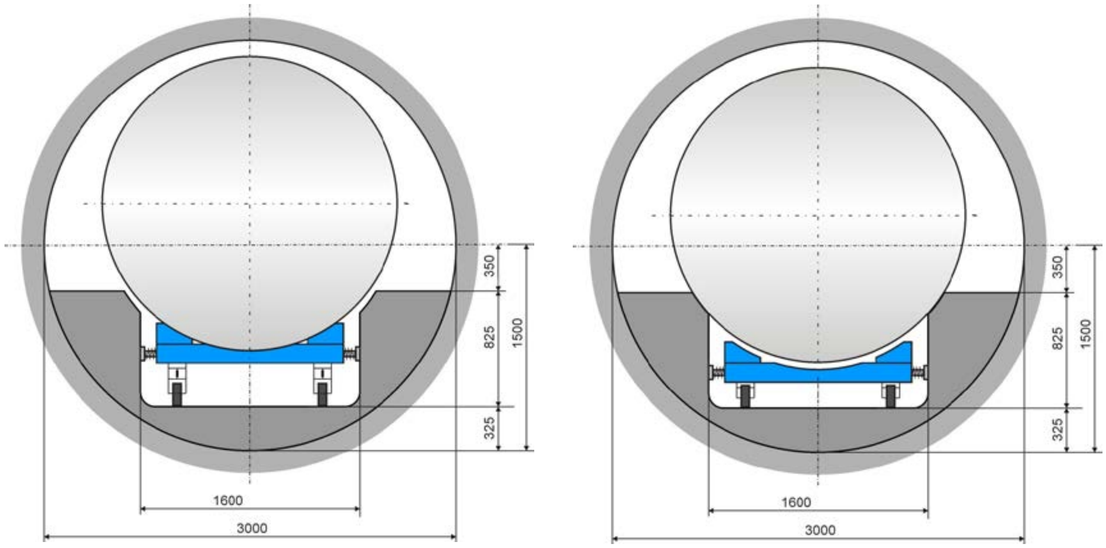

Fig. 8: Supercontainer and Trolley during transport and after emplacement

Further results of the development of the underground transport system were changed recommendations in regard to the diameter of access and disposal galleries. While turning of the largest waste package (6.25 m length and 2.25 m diameter) would be physically possible assuming gallery diameters of 6 m for the access gallery and 3 m for the disposal gallery, escape routes would be blocked during turning operation. Therefore an increased diameter of approximately 7 m for the access gallery was proposed at least for the C-Waste part of the repository.

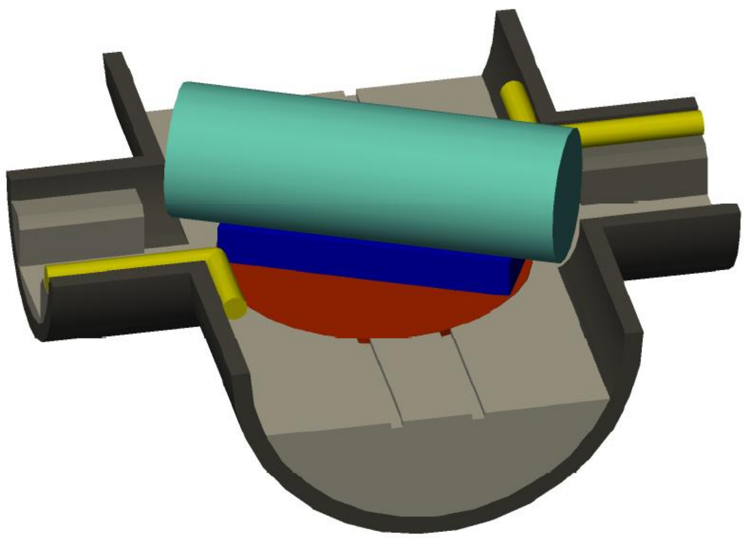

Fig. 9: C-Waste Supercontainer being rotated on the Turn Table for Subsequent Disposal

For the B-waste disposal fields only the diameter of the disposal galleries will need to be increased, as the reference diameter of 3.0 m leaves too little clearance between the waste package and the gallery and installation of ventilation ducts will be difficult. Also installation of pipes etc. required during backfilling operations will be problematic. A diameter of 3.5 m has been proposed for these galleries (Fig.10).

The final gallery diameters to be selected by ONDRAF/NIRAS will ultimately depend upon the Belgian regulatory framework that will have to be applied for implementation of the Belgian concept. Additionally other design alternatives, such as redesigning the intersection of the galleries could also impact the final selection by ONDRAF/NIRAS.

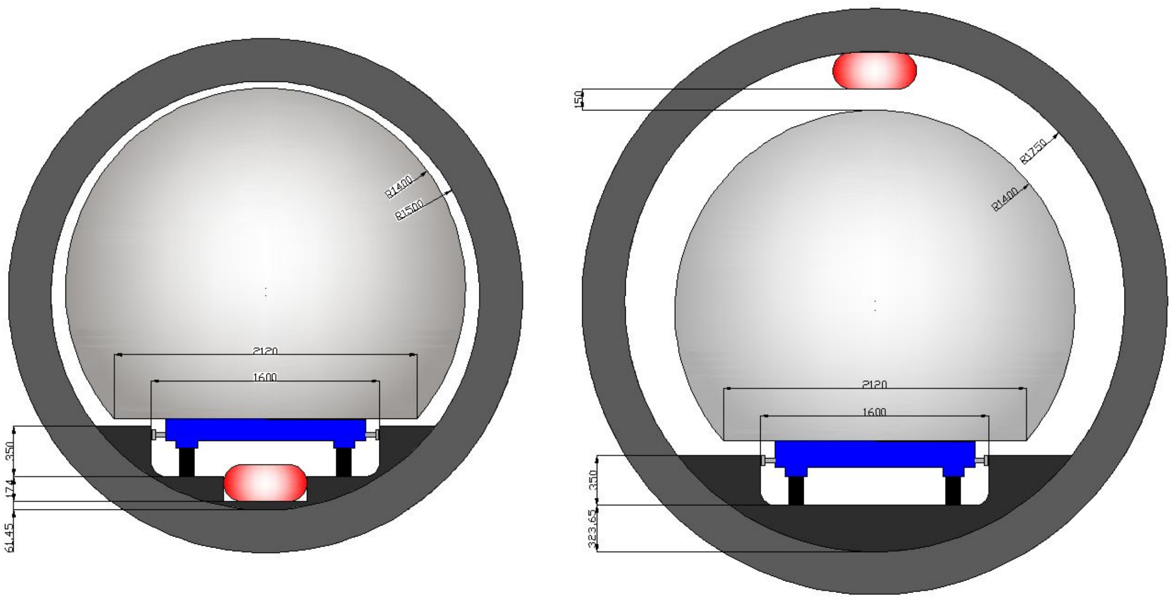

Fig. 10: Comparison of the situation for the current disposal gallery diameter of 3.0 m and the proposed increased disposal gallery diameter of 3.5 m

All main components of the underground transport system are based on proven technology and there is no doubt about the feasibility to carry out the disposal operations using the proposed system. An ongoing study on the mechanical loads on the floor structure during transport and waste emplacements also shows that no significant problems are to be expected in this area.

Repository Ventilation

Adequate ventilation of the underground repository is a prerequisite to guarantee safe and comfortable working conditions during the operational phase. Based on the experience from designing, constructing and operating the ventilation systems for the German geological disposal sites, first an analysis was made of the requirements of the ventilation system for the Belgian disposal concept. As the two repository sections, the B-waste field and the C-waste field will operated separately from each other and will not be open at the same time, the repository layout to be considered for the design of the ventilation system is a very simple one, consisting of two shafts connected by an access gallery and dead-end disposal galleries perpendicular to the access gallery. Subsequently a ventilation system that meets the defined requirements was developed. The system consists of a primary ventilation system generating a continuous airflow in the access gallery and shafts and an auxiliary ventilation system ventilating the dead end disposal galleries.

The proposed duct system in the disposal galleries is composed of 2 to 6 m long steel segments. The intake end of the disposal gallery ducts is installed ca. 10 m from the end of the gallery or backfilled gallery section. As the disposal galleries are backfilled and ducts segments are removed, the total duct length and thus the inherent resistance to airflow are reduced. To guarantee a constant airflow in the galleries the ducts are equipped with gates to regulate and balance the airflow inside the ducts.

The ventilation concept developed for the Belgian concept anticipates that ventilation air will flow into the repository through the respective service shafts, while main fans at the waste shaft on the surface will extract exhaust air through the waste shaft and discharge it through a diffusor to the outside environment. The disposal galleries are ventilated using dedicated ductwork installed along the entire gallery length. Fresh air enters into the disposal galleries through the gallery access and is removed via suction from the end of the gallery via the ventilation duct by using an auxiliary fan installed in the exhaust shaft. As Supercontainers are emplaced and the disposal galleries subsequently backfilled in a retreating fashion, the ventilation ducts are shortened accordingly.

The main challenge in the Belgian concept is designing a ventilation system that can be installed in the limited space available in the disposal galleries (see above). Therefore, the available space must be used as effectively as possible, provided that the diameter of the disposal galleries will not be increased (see above).

The proposed ventilation system is based on conventional technique and state-of-the-art equipment and provides adequate airflow for the personnel requirements of the subsurface facilities, including operations in the 1000 m long blind-ending disposal galleries and provides sufficient margin to assure personnel safety in unusual and emergency operation conditions. It can be implemented without the need for additional shafts in each emplacement field.

Backfilling

Following the current Belgian concept, the repository will be progressively closed as waste disposal progresses, by backfilling the filled disposal galleries (Fig. 11). Backfilling of the disposal galleries will be carried out in sections of approximately 30 m.

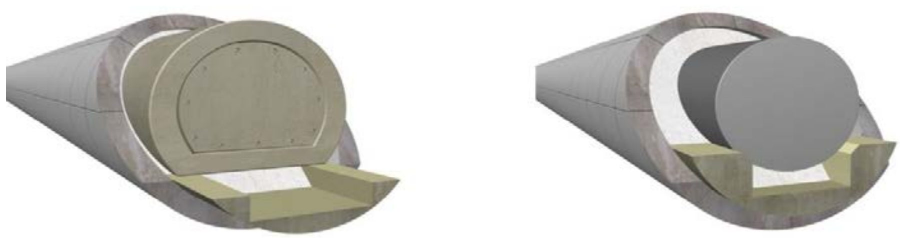

Fig. 11: Backfilled gallery section of a category B and C waste disposal gallery

After completion of all disposal operations, the access galleries and shafts are backfilled as well. Installation of seals at several locations in the repository is still an open issue and part of on-going R&D.

Repository backfilling is necessary to limit the amount of free water in the repository which is a regulator requirement in Belgium. The backfill also provides stability to the galleries and shafts and both backfill and seals help in compartmentalizing the repository, which is required to limit the consequences of human intrusion.

In regard to demonstrate the feasibility of the Belgian concept, it has to be confirmed that materials can be developed that fulfill the requirements for the future backfill material once it has been emplaced in the galleries and that it will be possible to produce the backfill material at the surface and pump it down into the repository because the restricted space underground will complicate the underground production and shaft transport of the fluid backfilling mixture. There is little experience for this kind of backfilling operation from the mining industry which could be used as confirmation of its feasibility. However, at the geological repository Morsleben in Germany, which is operated by DBE, a project has been carried out during the last years, which shows large similarities with the future task of backfilling the Belgian repository.

The Morsleben repository is a former rock salt and potash mine consisting of a widespread system of tunnels, cavities and blind shafts between 320 m and 630 m depth with a total void volume of more than 6 million cubic meters. To avoid stability problems, DBE has backfilled the central part of the mine with a concrete that was produced on-surface in a mixing plant constructed adjacent to one of the repository shafts and then pumped underground. The length of the pipelines ranged from 100 to 300 m on surface, 425 m along the shaft and up to 1200 m in the underground repository. At the end of the backfilling operations approximately 1 million cubic meters had been successfully backfilled, which demonstrated the feasibility of preparing a cementitious backfill at the surface and transporting it underground to the backfilling location [8].

In regard to a suitable backfill grout for the Belgian concept, there has been a lot of development in the past. The proposed backfill composition and its injection in a gallery was tested in the ESDRED Experiment [9], which consisted of a full scale (1/1) mock-up representing a 30 m long section of a disposal gallery that was installed at the surface. A heater was installed in a sand-filled steel tube to simulate a heat-emitting Supercontainer.

The experiment showed that it was feasible to prepare and inject grout into a disposal gallery at the required rate to prevent setting during backfill injection and that a filling degree of more than 98% could be achieved. However, it was also observed that the grout had ultimately failed to become hard, even after a curing period of several months

In an on-going R&D study DBE TECHNOLOGY is occupied with the development of a more robust backfill grout composition. The composition has to combine a sufficiently high flow-capacity to obtain a good filling degree with a satisfying hardening behavior. In addition, the compressive strength of the hardened material should be low enough to allow potential excavation of Supercontainers by using hydro-jet excavation methods in case retrieval of the waste would be necessary.

Because of its straightforward chemical compatibility with the disposal concept and the perceived better opportunities for achieving the industrial performance, the grout injection technique has been considered as the reference solution for the backfilling of the disposal galleries. The main constraints to be considered during the development of the backfilling material are:

Constraints related to (long-term) safety:

- No disturbance of the corrosion-protective characteristics of the buffer in the Supercontainer;
- No (low) heat insulation properties of the backfill;
- No introduction of organic materials that can give rise to migration-enhancing complexes;
- No excessive expansion or shrinkage;
- No chemical attack of the disposal drift wall.

Constraints related to feasibility:

- Physical properties of allow long-distance pumping and filling of small voids;
- Industrial performance of the production and backfilling operation must be feasible;
- Dust generation and water run-back should remain very limited;

- Low compressive strength, to keep the option of retrievability open.

The requirement of a low strength of the backfill material resulted in the selection of a 32.5 class cement according to European norm EN 197-1. Supplementary materials (SCM) were used to guarantee the formation of a dense network of hydration products. After evaluating the conformity of different SCM with the chemical requirements and their influence on the material properties, a test series was performed to study the tendency of different products to bleeding (segregation of excess water from the suspension) the decision was made in favor of silica fume. Sand with maximum grain size of 2 mm completed the range of solid ingredients, which were mixed with potable water.

The relative quantities of the material ingredients were estimated according to charts and tables documented in the common technical literature. Laboratory trial batches were performed to optimize the proportions and to create reference mixtures in conformity with the requirements. The testing of the material properties was carried out according to the following sequence: bleeding, segregation resistance, flow-capacity/workability, shrinkage, and strength.

When silica fume is used as SCM, it is important that it is dispersed and uniformly distributed in the mixture, which may require a longer mixing time than for other concrete or grout mixtures. The duration of the mixing process was further extended during the tests to simulate the flow process of the material from the batch plant to the galleries in the underground repository, and to obtain information about the time span the mixtures remained workable. In most cases, the suspensions were mixed between 0.5 and 1.5 hours.

The bleeding was investigated on the basis of the international ASTM C 940 standard by placing the fresh material in graduated cylinders and observing the changes in the grout volume and the accumulation of bleed water on the surface of the material over time. The segregation resistance was proven visually, after cutting cylindrical specimens along their vertical axis. Flow-capacity was determined by filling fresh material into a conical metal mold which was placed on a glass plate. The diameter of the cake developing after lifting of the mold then gives a measure or the flow-capacity (Fig. 12). Measurements of the flow angle of the fresh material surface in plastic boxes completed the investigations of the rheological material properties.

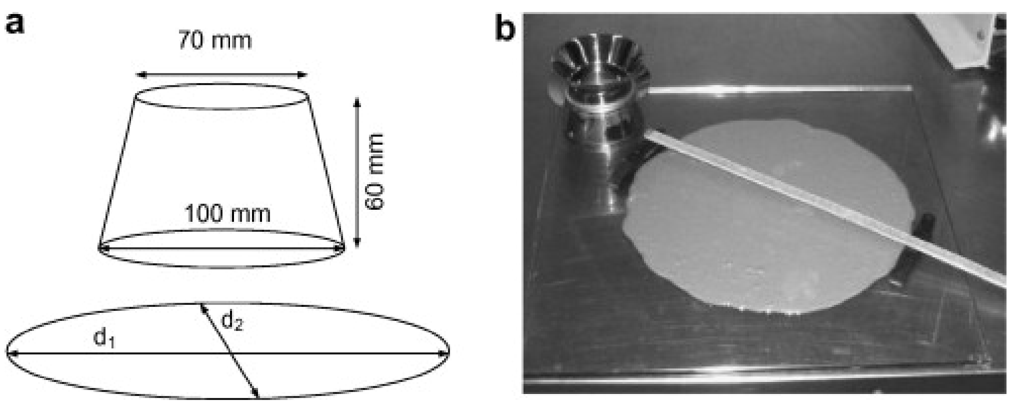

Fig. 12: Mini-slump flow test/ Mini-slump cone test. Schematic of a spread-flow test.
A: proportions of the Hägermann cone,
B: Example of an executed spread-flow test with a cement-silica fume-sand-mixture, showing the Hägermann cone with filling hopper according to EN 459-2.

Cubes and cylinders were casted for each mix proportion to determine strength values with a rebound hammer and their compressive strengths according to EN 12390-3. In accordance with the backfill practice, the material was not consolidated. The specimens hardened in closed molds at temperatures of 20 ± 2 °C and were tested at ages up to 100 days.

The test results for each material property were plotted in diagrams with the water-cement-ratio on the X-axis and the cement-SCM-ratio as the Y-axis. This procedure allows the determination of boundary lines, distinguishing between conformity and non-conformity of the mixtures. The combination of the diagrams leads to the definition of a boundary region showing those proportions of ingredients that can be used to produce a reference backfill material.

Transport mechanisms in cementitious materials, such as capillary suction, gas permeability, diffusion, and migration due to electrical potential gradients, depend on the porosity and the degree of saturation of the pores with solutions. In general, the pore space is not fully saturated. This fact is based on the input of air during the mixing process and the difference between chemical and autogenous shrinkage. The total porosity of the mixtures was calculated, considering a degree of cement hydration of 100 % and a water content of 25 wt.-% of the hydration products. It was assumed that the amount of reactive silica fume corresponds to 11 wt.-% of the cement content (EN 206-1). The values were used to estimate the chemical and autogenous shrinkage, which are low compared with conventional mortars due to the low content of reactive substances. Future laboratory work should obtain measurement results on the degree of saturation of the pore system.

It is assumed that the flow-capacity of the backfill material changes during the flow process from the batch plant into the underground galleries due to the compressive and shear stress generated in the backfill pipe. This influence, as well as the general pumpability, will be investigated by pumping the fresh material in a flow loop that will be equipped with pressure sensors. In the final step of this research study, experiments in a small scale (length 1 m, diameter 0.4 m) plexiglass setup will be carried out to simulate the flow of the backfill material in the underground galleries and to produce a larger specimen to further investigate segregation behavior and material properties.

CONCLUSIONS

ONDRAF/NIRAS' R&D feasibility program on geological disposal aims at demonstrating, at a conceptual level, that the disposal packages can be fabricated and that the repository can be constructed, operated and closed. In regard to repository operation most aspects that had been unsolved at the beginning of the R&D project have been investigated and solutions have been found. The main engineering challenges in the Belgian repository concept are size limitations on the underground facilities imposed by the mechanical behavior of the candidate host rock type (i.e., poorly indurated clay), which requires significant ground support. Optimization of the available space is therefore the most important aspect to be considered during the planning of the future operation. DBE TECHNOLOGY developed concepts for a hoisting system for shaft transport of the waste packages, an underground transport and waste emplacement system and a ventilation system. All systems for transport and ventilation are based on state-of-the-art equipment or components that have been built and tested in a 1/1 scale during R&D work carried out by DBE in connection with the German repository projects at Gorleben and Konrad. Accordingly, at the present stage of planning for none of the proposed transport and ventilation systems and their main components significant open questions or doubts remain in regard to their feasibility.

In regard to closure operation, the development of a reference backfill material is in its final stage. The hitherto gathered results indicate that the definition of a reference backfill composition that fulfills the requirements will be possible, but the study still has to be completed.

The most important remaining open question is the design and construction of seals in the galleries and shafts, which is the topic of a further still on-going operational feasibility study.

REFERENCES

1. ONDRAF/NIRAS, 2011. Waste Plan.
2. ONDRAF/NIRAS, 2009. The Long-term Safety Strategy for the Geological Disposal of Radioactive Waste, ONDRAF/NIRAS report NIROND-TR 2009 12 E.
3. ONDRAF/NIRAS, 2010. Feasibility Strategy and Feasibility Assessment Methodology for the Geological Disposal of Radioactive Waste. ONDRAF/NIRAS Report, NIROND-TR 2010-19 E.
4. Belgatom, 2005. Conceptual layout for a disposal facility for category B & C waste in Belgium: Stage 1 – Overview, Belgatom Report.
5. Van Marcke, P., Li, X.L., Bastiaens, W., Verstricht, J., Chen, G., De Preter, P. and Leysen, J., 2013. The design and installation of the PRACLAY In-Situ Experiment, EURIDICE Report 13-129.
6. Bastiaens, W., Bernier, F., Buyens, M., Demarche, M., Li, X.L., Linotte, J.-M. and Verstricht, J., 2003. The extension of the HADES underground research facility at Mol, Belgium: The construction of the connecting gallery, EURIDICE Report 03-294.
7. Haverkamp, B., Biurrun, E., Filbert, W., Engelhardt, J., 2010. Technical Support for the R&D Feasibility Programme for the Geological Disposal of Category B&C Radioactive Waste Lot 3 – Operation – State-of-the-Art Report Final Draft, DBE TECHNOLOGY GmbH Report: TEC-03-2010-Z.
8. Preuss, J., Eilers, G. Mauke, R., Müller-Hoeppe, N., Engelhardt, H.-J., Kreienmeyer, M., Lerch, C. and Schrimpf, C., 2002. Post-closure safety of the Morsleben repository, WM2002 Conference, February 24-28, 2002, Tucson, Arizona, USA.
9. Commission of the European Community, 2009. ESDRED Final Summary Report and Global Evaluation of the Project, Mod6-WP4-D6, Brussels.