Evaluation of Container Placement Methods for the Conceptual Design of a Deep Geological Repository

NWMO TR-2010-20

December 2010

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ABSTRACT

Title: **Evaluation of Container Placement Methods for the Conceptual Design of a Deep Geological Repository**
Report No.: **NWMO TR-2010-20**
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Abstract

Three generic used fuel container placement methods for a deep geological repository have been evaluated in a qualitative manner based on technical feasibility, safety, siting, monitoring and retrieval for application in crystalline rock, hard sedimentary rock and soft sedimentary rock. The three generic used fuel container placement methods, in-floor borehole, horizontal borehole and horizontal tunnel, are derived from a review of repository concepts being developed by national radioactive waste management organizations. Each container placement method has a number of variants, which depend in part on national program designs and site specific conditions. Where these variants are significantly different, they are assessed individually.

<u>In-floor Borehole Placement Method:</u>
The in-floor borehole placement method has been well developed and demonstrated for a deep geological repository in crystalline rock. It is the reference container placement method for crystalline rock in Sweden and Finland and there are only minor variations in design amongst the national programs. The in-floor borehole placement method is also considered to be suitable for hard sedimentary rock, but may not be suitable for soft sedimentary rock without significant ground support and other engineering modifications.

<u>Horizontal Borehole Placement Method:</u>
The horizontal borehole placement method is being developed and demonstrated for a deep geological repository in crystalline rock and soft sedimentary rock. It is the alternative container placement method for crystalline rock in Sweden and Finland and it is the reference container placement method, with borehole liners, for soft sedimentary rock in France and Belgium. There are significant variations in design amongst these national programs primarily driven by the potential site conditions and the level of effort associated with monitoring and retrieval of containers. It is also considered to be suitable for hard sedimentary rock.

<u>Horizontal Tunnel:</u>
The horizontal tunnel placement method has been developed specifically for hard sedimentary rock and is also considered suitable for soft sedimentary rock with the addition of tunnel liners for ground support. It is the reference container placement method for sedimentary rock in Switzerland. The principal technical feasibility and safety issues relate to achieving a sufficiently high bentonite buffer as-placed dry density or ambient groundwater salinity to effectively suppress microbial activity and the potential of microbially-influenced corrosion of containers in the repository. The placement method might not be appropriate in crystalline rock since both the achievable dry density of the bentonite pellets and the groundwater salinity are likely to be too low to suppress microbial activity near the containers.

The results from this assessment suggest that all three placement methods would meet the general technical evaluation criteria within the constraints outlined above.

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1. INTRODUCTION

1.1 BACKGROUND

The Nuclear Waste Management Organization (NWMO) has a technical program to support implementation of Adaptive Phased Management. The NWMO’s technical program includes advancing the technology associated with a deep geological repository for used fuel in a suitable geological formation, such as crystalline rock or sedimentary rock.

The Canadian technical programs in support of deep geological repository technology have been ongoing since the 1970s and have included a number of studies of conceptual repository designs and used fuel container placement methods for deep geological repositories in crystalline rock (e.g., Simmons and Baumgartner 1994, Baumgartner et al. 1996, CTECH 2002, RWE NUKEM 2003 and RWE NUKEM 2004a and 2004b) and in sedimentary rock (e.g., RWE NUKEM 2004c and 2004d).

The objective of this report is to evaluate generic used-fuel container placement methods for application in a deep geological repository in crystalline rock and sedimentary rock using general technical evaluation criteria associated with technical feasibility, safety, siting, monitoring and retrievability.

1.2 DEEP GEOLOGICAL REPOSITORY DESIGN CONCEPT

A conceptual illustration of the in-floor borehole placement method for a Canadian deep geological repository for used nuclear fuel is shown in Figure 1. The repository concept entails encapsulating used-fuel bundles in durable containers and sealing the containers in a repository located at a depth of about 500 m in a suitable geological formation. The base case inventory of used nuclear fuel for conceptual design studies is 3.6 million used-fuel bundles (NWMO 2005).

In general, the NWMO’s concept of a deep geological repository incorporates a system of engineered and natural barriers. The engineered barriers include the used nuclear fuel, used-fuel container and repository sealing systems. The natural barrier includes the near-field and far-field geosphere, as well as any surface features in the biosphere. Stress and temperature changes to the near-field rock mass surrounding the repository during construction and operation of the repository will need to be considered in the engineering performance analyses and safety assessment of the repository.

The repository would comprise access by shaft or ramp to a network of horizontal tunnels/placement rooms designed to suit the structure and characteristics of the host geological formation, groundwater flow, and other subsurface conditions at the particular site. The used-fuel containers would be placed either within the placement rooms/tunnels or in placement boreholes drilled from the rooms. Clay-based sealing materials would be used to surround the containers and to fill the remaining void in each placement room/tunnel/borehole. When containers are sealed in place, the radioactive decay of the used fuel would raise the temperature of the repository and surrounding rock mass and the groundwater would begin to move into the unsaturated portions of the repository and surrounding rock.

After all placement rooms/tunnels/boreholes are filled with the desired number of used-fuel containers and sealed, there would be a suitable period of post-container-placement monitoring to confirm that the facility is performing as expected.

Schematic representations of three potential container-placement methods for a deep geological repository are shown in Figure 2. The three potential container placement methods are drawn from conceptual designs for deep geological repositories developed by the NWMO and other national radioactive waste management organizations.

After a sufficient period of post-container-placement monitoring, and following regulatory approvals and other considerations, all remaining tunnels, shafts/ramps, service areas and exploration boreholes would be backfilled and sealed such that long-term safety of the facility would not depend on institutional control. The repository concept includes the provision to retrieve used-fuel containers during the preclosure period, postclosure monitoring of the repository and its surroundings, and a feasible approach to postclosure retrieval of used-fuel containers.

NMWO is considering both the copper and steel used-fuel container designs for use in a deep geological repository. The copper used-fuel container design is a dual-vessel container (Figure 3) comprising an outer copper corrosion-barrier vessel, an inner steel load-bearing vessel and interior baskets to hold the used fuel bundles (Maak and Simmons 2005). The steel used-fuel container design comprises a single steel vessel with a seal-welded closure and interior baskets to hold the used fuel bundles (Figure 4). Used-fuel containers with either a copper or a steel corrosion barrier could be applied in any variant of a placement method.

1.3 POTENTIAL HOST ROCK MEDIA

The ultimate end-state of Adaptive Phased Management is centralized containment and isolation of used nuclear fuel in a deep geological repository in a suitable rock formation in Canada. The potentially suitable host geological formation could have characteristics ranging from those associated with crystalline rock (e.g., plutonic rock of the Canadian Shield) to those associated with sedimentary rock (e.g., shale or limestone).

The selection of a specific design and a placement method for a deep geological repository would likely be dependent on the conditions of the site at which they would be applied. In May 2010, the NWMO launched a process for selecting a site for Canada's deep geological repository for used nuclear fuel. Therefore, this assessment of container placement methods and variants within some placement methods is generic in nature and identifies issues that would have to be considered in applying each placement method to a deep geological repository design in Canadian conditions.

In this report, "crystalline rock" is assumed to have the characteristics of sparsely fractured or moderately fractured granitic plutons located in the Canadian Shield.

Crystalline rock is a generic term for igneous and metamorphic rocks as opposed to sedimentary rocks. Igneous rocks are formed at considerable distance beneath the surface of the Earth by the cooling and crystallisation of magma. Metamorphic rocks are formed by physical and chemical alteration of pre-existing rocks. The rock creep rate will be extremely low and will not affect the excavation stability during the life of the repository. Excavation stability will be affected by in situ rock properties and in situ stress. In crystalline rock, an underground opening (e.g., tunnel, room, borehole) at repository depth can be prepared and maintained throughout the preclosure period by normal maintenance without substantial rock support (e.g., grouting, liners, shotcrete). There may be local areas that would require application of ground control methods to address geological and structural conditions (e.g., rock spalling, extensive local fracturing).

Sedimentary rock is formed from the consolidation of deposited sediments due to: erosion and displacement (e.g., sandstone and shale); precipitation from solution (e.g., salt and gypsum); and organic processes (e.g., limestone and coal). From a constructability perspective, a deep geological repository for used fuel could be constructed in a sedimentary rock formation (RWE NUKEM 2004c). For completeness in reviewing container placement methods, the sedimentary rocks are subdivided into hard and soft sedimentary rocks.

In **hard sedimentary rock**, the rock creep rate will be very low and will not affect excavation stability during the operational period of the repository. The stability of the excavation will be influenced by the in situ rock properties and in situ stress. In hard sedimentary rock, an underground opening (e.g., tunnel, room, borehole) at repository depth can be prepared and maintained throughout the preclosure period by normal maintenance without substantial rock support (e.g., liners, substantial application of shotcrete). There may be local areas that would require application of ground control methods to address geological and structural conditions (e.g., rock spalling, extensive local fracturing).

In **soft sedimentary rock**, the rock creep rate will be significant and will affect the stability of underground excavations at repository depth. In soft sedimentary rock, an underground opening (e.g., tunnel, room, borehole) at repository depth can be prepared and maintained throughout the preclosure operational period only with the use of substantial rock support (e.g., liners, substantial application of shotcrete).

2. CONTAINER PLACEMENT METHODS

The principal used-fuel container placement methods were derived from a review of repository concepts being developed by national radioactive waste management organizations and are described in this section.

2.1 IN-FLOOR BOREHOLE PLACEMENT METHOD

As the recent concepts for deep geological repositories using the in-floor borehole placement include placement arrangements that are very similar, there is only one in-floor borehole placement method (i.e., without variants) assessed in this report.

For the in-floor borehole placement method, the used-fuel container would be placed vertically into a borehole drilled into the floor of a placement room. The borehole would be designed to receive one container and the highly compacted bentonite portion of the placement room sealing system. A portion of the highly compacted bentonite would be placed in the borehole as precompacted discs and rings. The container would be placed in the opening within the highly compacted bentonite rings. The borehole would be filled to the placement room floor with either additional highly compacted bentonite or dense particulate bentonite gap fill and possibly covered with dense backfill. When all boreholes in a placement room are filled, all remaining voids in the room would be backfilled and the room access opening(s) sealed with a bulkhead. The in-floor borehole placement method has been studied extensively in Canada, Sweden, Finland and Japan for use in the development of the deep geological repository concept in crystalline rock.

The in-floor borehole placement method (KBS-3V, Figure 5) is the reference placement method for SKB (Swedish Nuclear Fuel and Waste Management Company) and Posiva (Posiva Oy, the Finnish organization responsible for the long-term management of spent nuclear fuel) in the development of their deep geological repository concept in crystalline rock (SKB 1999). In the KBS-3V design, the copper-shelled used-fuel containers are placed in vertical boreholes, surrounded by highly compacted bentonite rings and discs. SKB, in association with Posiva and other waste management organizations, has been conducting large-scale in situ experiments in the Äspö Hard Rock Laboratory (HRL) in Sweden to develop and demonstrate appropriate technologies. With regard to the placement method, these experiments have demonstrated the placement technologies for used-fuel container, sealing system and some aspects of the technologies for used-fuel container retrieval.

The in-floor borehole placement method has also been studied in Canada for many years (e.g., Simmons and Baumgartner 1994, RWE NUKEM 2003). The earlier designs considered a smaller container, a larger used-fuel inventory and a highly compacted bentonite/sand sealing system adjacent to the container. RWE NUKEM (2003) presented a revised conceptual design for placement of a larger-capacity copper-shell container (Figure 3) using the in-floor borehole placement method (Figure 6). In the RWE NUKEM design, the used-fuel containers are surrounded by highly compacted 100% bentonite discs and rings. The gaps between the container and the highly compacted bentonite and the gaps between the highly compacted bentonite and the borehole rock wall would be filled with highly compacted granular bentonite gap fill material. Additional highly compacted bentonite discs would cover the used-fuel container. Following placement of all containers in a borehole, the room would be backfilled with blocks of dense backfill surrounded by light particulate backfill. The main reason for replacing bentonite/sand buffer with 100% bentonite buffer in the conceptual design is to improve the capability of the buffer to suppress microbial activity and the potential for microbially-influenced corrosion of the used-fuel containers.

2.2 HORIZONTAL BOREHOLE METHODS

Concepts for deep geological repositories using the horizontal borehole placement method have been developed recently. These are sufficiently different that three variants of this placement method are assessed in this report.

2.2.1 KBS-3H-type Horizontal Borehole Method

The KBS-3H horizontal borehole placement method has been studied by SKB and Posiva as an alternative method for their reference in-floor borehole placement method for a crystalline rock repository (Lindgren et al. 2003). In the KBS-3H design, “super container packages” are placed inside horizontal boreholes. In a super-container package, the copper-shell used-fuel container is enclosed in bentonite buffer inside a perforated sleeve (Figure 7). The super-container package is placed in the borehole using specially designed deposition equipment. Prototype deposition equipment to place the super-container and spacer elements in the borehole has been tested within the scope of a European Commission 6^{th} Framework Integrated Project, ESDRED, at the Äspö Hard Rock Laboratory (SKB 2007).

RWE NUKEM (2004a) adapted the KBS-3H conceptual design to a specific Canadian reference used fuel container and the specific requirements of the Canadian placement room sealing system. Their version of a super container package (Figure 8) comprises:

- the used fuel container;
- highly compacted bentonite buffer; and
- a perforated carbon steel sleeve to prevent damage to the highly compacted bentonite buffer.

The borehole is filled with super-containers separated by highly compacted bentonite spacers sized to limit the maximum container surface temperature to 100˚C (Figure 9). One operational item included by RWE NUKEM is the use of a curved section of tunnel from the access tunnel leading the placement borehole collar to provide for equipment operation and to reduce the risk of radiation streaming into the access tunnels (Figure 9).

2.2.2 ANDRA-type Horizontal Borehole Placement Method

ANDRA (French National Radioactive Waste Management Agency) is responsible for the long-term management of radioactive waste produced in France. ANDRA has been conducting a research and development program for a deep geological repository concept to be applied in the Meuse/Haute-Marne region in the Callovo-Oxfordian sedimentary rock formation (depth – 420 m to 550 m) (ANDRA 2005a).

ANDRA has developed a variation of the horizontal borehole placement method that provides a safe and reversible deep geological repository system and associated equipment for high-level waste (type C waste), intermediate-level waste (type B waste) and non-reprocessed spent fuel (type CU material). In this report, ANDRA’s technologies for placement of steel containers containing four spent fuel assemblies are discussed since these containers are of comparable size to the typical Canadian used-fuel container. Information on the containers for B waste, C-waste and one spent fuel assembly is available in ANDRA (2005a).

Four assemblies of spent fuel would be placed in a cylindrical steel container filled with a cast iron insert (Figure 10). The steel container with a wall thickness of 110 mm is intended to provide a water barrier for at least 10,000 years.

ANDRA has assessed either horizontal or vertical cells in a repository in the clay formation (ANDRA 2005b) and has selected the horizontal borehole placement method as the reference repository design. ANDRA prefers the horizontal placement arrangement because it maximizes the thickness of undisturbed clay formation above and below the repository and minimizes the volume of openings excavated and subsequently sealed.

The horizontal placement boreholes in the ANDRA conceptual repository design are dead-end, about 40 m long, and about 3.3 m in diameter. Each borehole would contain a single row of spent fuel containers. The cross section and longitudinal section through a placement borehole are shown in Figures 11 and 12, respectively, and comprise:

- a 25 mm to 30 mm thick steel tube that lines the 3.3-m-diameter borehole, constitutes the thrust tube during excavation, protects personnel during construction and supports the other engineered barrier segments;
- buffer rings (800-mm-thick, 70/30 clay/sand buffer) inserted into the borehole (see Figure 11) after the installation of the steel tube;
- steel sleeve segments (30-mm-thick), welded together inside the tunnel, installed inside the buffer rings (Figure 13); and
- the steel containers holding four spent fuel assemblies separated by buffer spacer assemblies.

The steel container could be placed inside the steel sleeve using a specific air-cushion device. In this case, the container is raised by air cushion units fixed to a cradle, which is then pushed by a self-propelled carriage (Figure 13) (ANDRA 2005b). The principle of this placement process has been successfully tested in surface laboratories as part of a European Commission 6th Framework Integrated Project, ESDRED.

In order to comply with the French law requiring process reversibility at all stages of deep geological repository, there is a gap between the steel sleeve and the steel container (Figure 11) that would facilitate container removal with minimal effort (i.e., easily reversible).

2.2.3 ONDRAF/NIRAS-type Horizontal Borehole Placement Method

ONDRAF/NIRAS (Belgian Agency for Management of Radioactive Waste and Enriched Fissile Materials) is responsible for the development of a deep geological repository for radioactive waste in clay formations in Belgium. The Boom Clay beneath the Mol-Dessel nuclear zone in Belgium is the reference site for research and development purposes and the location of the Mol underground laboratory.

The current ONDRAF/NIRAS reference design for the deep geological repository is another variant of the horizontal borehole placement method (Bel et al. 2006). High-level vitrified waste and spent fuel, are sealed in waste containers and packaged into super containers consisting of two waste containers in a carbon steel overpack surrounded by a Portland-cement-based buffer within a stainless steel outer vessel. The super-containers are placed in horizontal boreholes (about 2 m in diameter) that are lined with concrete wedge blocks to form a concrete liner to provide structural stability in the relatively soft Boom clay (Figure 14). The carbon steel overpack is intended to contain the radioactive waste and prevent it from coming into contact with external fluids for the duration of the thermal phase of the repository. The Portland cement-based buffer will provide a highly alkaline (i.e., high pH) chemical environment that would passivate the external surface of the steel overpack for thousands of years and inhibit corrosion of the steel overpack during the thermal-transient phase of repository evolution. For vitrified waste, the duration of the thermal phase is a few hundred years and for spent fuel it is a few thousand years.

2.3 HORIZONTAL TUNNEL PLACEMENT METHODS

Concepts for deep geological repositories using the horizontal tunnel placement method have been developed recently. These are sufficiently different that two variants of this placement method are assessed in this report.

2.3.1 CTECH-type Horizontal Tunnel Placement Method

CTECH (2002) described a variant of the horizontal tunnel placement method for a hypothetical Canadian crystalline rock repository with 324 used-fuel-bundles in a “super-container-type” assembly. The used-fuel inventory was 3.6 million bundles. A sealing system, using highly compacted bentonite buffer within the “super-container-type” assembly, was supported and surrounded in the tunnel by a block structure of dense backfill and a particulate light backfill. In this repository study, two “super-container-type” assemblies would be placed abreast along the length of a placement tunnel spaced to meet the thermal and mechanical design criteria (e.g., CTECH tunnel cross section in Figure 15).

The sealing system in the placement room proposed by CTECH (Figure 15) consists of complex array of sealing components including shaped-blocks of highly-compacted bentonite, 50/50 bentonite/sand, and dense backfill, pneumatically placed light backfill material, and low alkalinity concrete. This placement method would be applied in the following steps.

- The room would be constructed and the concrete floor would be poured.
- Progressively, retreating from the extreme end of the placement room to the entrance:
  - an array of blocks would be placed to about the mid-height of the room with a slot open to the floor under the location of each super-container assembly so that a dolly could be used to carry each container assembly to its rest location on the array of blocks;
  - the super-container assemblies would be moved into place on the dollies and lowered onto the assemblages of blocks simultaneously to minimize the movement of the block array as the load of the two containers is applied;
  - the dollies would be withdrawn and shaped blocks would be inserted to fill the slots between the super-container assemblies and the floor to the floor and to cover the super-container assemblies to the depth allowed by the working clearances within the room; and
  - the voids between the outer perimeter of the block array and the room perimeter would be filled with pneumatically or mechanically placed light backfill material.
- When a placement room is filled, the entrance to the room would be sealed with a concrete and highly compacted bentonite bulkhead.

2.3.2 NAGRA-type Horizontal Tunnel Placement Method

NAGRA (National Cooperative for the Disposal of Radioactive Waste, Switzerland) is responsible for the development of deep geological repository concepts for radioactive waste in both crystalline and clay host rock (in particular Opalinus Clay) in Switzerland. Opalinus Clay is a shale (claystone) formation present in northern Switzerland at a depth of about 540 m to 650 m with a formation thickness of about 115 m. Switzerland has two major underground research laboratories: Grimsel (crystalline rock); and Mont Terri (Opalinus Clay) although NAGRA's current focus is on the Opalinus Clay sedimentary rock formation.

As shown in Figure 16, each 150-mm-thick carbon steel container of spent fuel, 1.05-m in diameter and 4.6-m-long and with a mass of 26 Mg, would be placed on top of a highly compacted bentonite pedestal inside 2.5-m-diameter horizontal tunnels. If high-level radioactive waste is being placed in the repository, the containers would be 0.94-m in diameter and 2-m long with a wall thickness of 250 mm, having a mass of 8.4 Mg. The spacing between containers of either type would be 3 m. NAGRA has specified that the minimum design lifetime is 1,000 years for the steel container, although the lifetime assessment performed by Johnson and King (2003) indicates an expected container service life of at least 10,000 years.

The container would be placed onto a highly compacted bentonite pedestal inside the horizontal tunnel and the remaining voids around the container in the placement tunnel would be backfilled with granular bentonite material having a moisture content of about 2%, and would comprise 80% by volume very dense pellets (about 2.1 to 2.2 g/cm^3) and 20% bentonite powder. Upon placement, NAGRA expects the granular material to have an average dry density of 1.5 g/cm^3. When a placement tunnel is filled with the intended number of containers, the tunnel is sealed at the ends.

NAGRA expect that rock bolts and mesh will be adequate for tunnel support. If necessary, concrete or polymer liners may be applied for access and container placement tunnel support (NAGRA 2002).

Retrieval of containers during the operational and postclosure phases is considered to be possible by NAGRA (Johnson and King 2003). Excavation into the bentonite to retrieve the containers is considered to be feasible for an extended period of time.

NWMO has begun assessing the potential for a deep geological repository in a Canadian environment using a NAGRA-type horizontal tunnel placement method. NWMO's microbial experiments have indicated that for a low-salinity environment (e.g., < 60 g NaCl/L), as would be expected in some crystalline rock formations, a bentonite dry density of ≥1.6 g/cm^3 would be required to suppress microbial activity and microbially influenced corrosion of the containers under aerobic conditions (Stroes-Gascoyne et al. 2006). NAGRA indicates that the particulate buffer density would be in the order of 1.5 g/cm^3 and hence would not be sufficiently high to suppress microbial activity and to inhibit microbially-influenced corrosion of the containers in crystalline rock. The in-situ groundwater/porewater salinity in Canadian sedimentary rock is expected to be ≥100 g NaCl/L, which would be sufficiently high to suppress microbial activity and microbially-influenced corrosion of containers. Thermal and mechanical sensitivity studies by Guo (2010, 2008) indicated that a thermally and mechanically acceptable deep geological repository arrangement could be achieved in Canadian hard sedimentary rock.

3. TECHNICAL EVALUATION FACTORS FOR EVALUATING THE CONTAINER PLACEMENT METHODS

In general, the used-fuel container placement methods can be grouped into either vertical or horizontal placement. The placement methods use mechanically excavated boreholes (if boreholes are part of the placement method) and either mechanically excavated or drill-and-blast excavated placement room/tunnels. Thus the three generic placement methods, two with variants, included in this technical assessment, are the:

- In-floor Borehole placement method;
- Horizontal Borehole placement method;
  - KBS-3H-type,
  - ANDRA-type, and
  - ONDRAF/NIRAS-type; and
- Horizontal Tunnel placement method;
  - CTECH-type, and
  - NAGRA-type.

These container placement methods are evaluated in a qualitative manner using the following general technical evaluation criteria.

- **Technical Feasibility** – considers the extent to which each placement method has been studied and demonstrated for a particular rock type, therefore the level of confidence that the placement method is practicable in that rock type, and the extent to which the placement method has been studied and demonstrated.
- **Siting** – considers specific constraints that a placement method might impose in selecting technically suitable sites for each of the subject rock types in Canada.
- **Safety** — consider the influence of the placement method on the occupational and public safety, both preclosure and postclosure.
- **Monitoring** – considers the amenability of each placement method to application of a monitoring program in the preclosure and postclosure periods.
- **Retrieval** – considers the practicability of retrieving used-fuel containers from a sealed placement room using each placement method and the extent to which aspects of retrievability have been studied and demonstrated.

For each rock type, the evaluation will provide an overall qualitative assessment of the general technical evaluation criteria listed above.

4. EVALUATION OF CONTAINER PLACEMENT METHODS FOR APPLICATION IN CRYSTALLINE ROCK

4.1 IN-FLOOR BOREHOLE PLACEMENT METHOD

For the in-floor borehole placement method, the used-fuel container is placed in a vertical borehole mechanically excavated into the floor of a placement room and surrounded by a simple buffer sealing system that consists mainly of highly compacted bentonite rings and discs.

4.1.1 Technical Feasibility

In addition to work done in Canada, relevant technologies for the in-floor borehole placement method for a deep geological repository in crystalline rock are being developed and demonstrated by national radioactive waste management programs in Sweden (SKB) and Finland (Posiva). It is the reference placement method of SKB and Posiva for their crystalline rock, deep geological repository concept.

The sealing system in the placement borehole is a simple design consisting mainly of highly compacted bentonite discs and rings. A method of placing the sealing materials and the used-fuel container inside the in-floor borehole has been developed and demonstrated in a non-radioactive environment by SKB at the Äspö Hard Rock Laboratory in Sweden. In NWMO's application, the placement borehole sealing system would likely require the use of a gap fill material between the used-fuel container and highly compacted bentonite discs and rings and between the highly compacted bentonite discs and rings and the borehole wall. This gap fill would also be beneficial for sealing any breakouts that may occur in the borehole wall. The composition, placement and as-placed characteristics of this gap fill material must be developed and demonstrated.

The simplicity of the sealing system in the placement borehole and in the placement room facilitates modeling of the thermal, hydraulic and mechanical behaviour of the repository.

In a crystalline rock deep geological repository, the access tunnels and the placement rooms would be excavated using a careful drill-and-blast method and the placement boreholes would be excavated by a mechanical boring method to achieve a high borehole wall quality. Both these excavation methods have been used extensively in mining and civil engineering projects and in underground research laboratories to support crystalline rock repository development. Examples include the excavation quality and response studies at Atomic Energy of Canada Limited's Underground Research Laboratory, SKB's Äspö Hard Rock Laboratory, and other facilities (e.g., Martin and Read 1996, Read and Chandler 2002, Bäckblom 2008).

4.1.2 Siting

The in-floor borehole placement method would require excavated placement rooms that would be, in general, larger in cross section than the boreholes of the horizontal borehole (Section 4.2) and the horizontal tunnel (Section 4.3) placement methods, and would also require a bored vertical borehole for placement of each used-fuel container. This would result in a larger volume of excavation and of sealing material. Although this difference is likely within a factor of two, the siting program would have to confirm the availability of an adequate volume of the rock for the repository using the chosen placement method (likely a minor factor in site screening).

In highly stressed or low-strength crystalline rock, the potential for rock breakouts on the borehole wall and near the intersection between the borehole and the tunnel floor would need to be assessed. High stress concentrations are anticipated at these locations in the repository. Breakouts would alter the rock surfaces and would require attention during borehole and placement room sealing.

If the rate of water seepage into a placement area (e.g., horizontal or vertical borehole, or horizontal tunnel) is high enough, it could affect the placement and thus the as-placed properties of the sealing materials. This could impact the performance of the placement borehole or tunnel sealing system and therefore the repository. This issue would be important for all placement methods in crystalline rock with water-bearing fractures, although the in-floor borehole method is more tolerant to water seepage than the horizontal borehole or horizontal tunnel placement methods. With the in-floor borehole placement method, either the seepage area can be isolated from container placement activities or, if the seepage is into a placement borehole, the borehole can be sealed without a used-fuel container.

4.1.3 Safety

The public and occupational safety of a deep geological repository concept using the in-floor borehole placement method in crystalline rock media during the preclosure period has been analyzed by Grondin et al. (1994). This repository concept was for a 10.1 million used-fuel bundle inventory, a 72-bundle used-fuel container and a different repository sealing system. The study indicates that effects on the public and workers from preclosure operations would be well within regulatory limits and guidelines or could be readily mitigated to be well within the regulatory limits or guidelines.

Postclosure public safety of a deep geological repository using the in-floor borehole placement method has been assessed in a Canadian crystalline rock geosphere for a 10.1 million used-fuel bundle inventory, a 72-bundle used-fuel container and a different repository sealing system (AECL 1994). This postclosure safety assessment found that the estimated dose rates to the public were well below the regulatory limit for the assumed site.

For the current deep geological repository concept using the in-floor borehole placement method, the used-fuel container would be surrounded by highly compacted bentonite discs and rings in the borehole. It is expected that the highly compacted bentonite buffer will have a dry density of at least 1.6 g/cm^3 and a saturated density of at least 2.0 g/cm^3, which is adequate to suppress the microbial activity at or near the container surface and thereby the potential for microbially-influenced corrosion of the containers (Stroes-Gascoyne et al. 2006 and Stroes-Gascoyne and Hamon 2008). This current deep geological repository concept should provide postclosure safety that is similar to that assessed by AECL (1994).

4.1.4 Monitoring

The monitoring program for a deep geological repository in any host media could be developed in the framework proposed by Simmons (2006). The ability to design a system to meet monitoring requirements for a deep geological repository using the in-floor borehole, the horizontal borehole, or the horizontal tunnel placement methods are expected to be similar.

4.1.5 Retrieval

The in-floor borehole placement method is the only placement method that allows the retrieval of an individual container without the potential need to retrieve a large number of containers within a room. Some aspects of the retrieval of a used-fuel container from an in-floor borehole configuration have been successfully demonstrated by SKB at Äspö Hard Rock Laboratory (Nirvin 2007). However, it may be necessary to remove a significant volume of placement room sealing material to retrieve a single container.

4.2 HORIZONTAL BOREHOLE PLACEMENT METHOD

The three variants of the horizontal borehole placement method considered in this report are summarized below.

KBS-3H-type variant of the horizontal borehole placement method

For the KBS-3H type horizontal borehole placement method, being developed by SKB and Posiva, used-fuel super-container packages are placed in a horizontal borehole. In a super-container package, a copper used-fuel container is enclosed in bentonite buffer inside a perforated steel sleeve. The whole package is placed in the borehole and is separated from the next super-container package using highly compacted bentonite spacer assemblies.

ANDRA-type variant of the horizontal borehole placement method

ANDRA has developed a variant of the horizontal borehole placement method that provides a reversible deep geological repository system. The horizontal placement boreholes are dead-end, about 40 m long, and about 3.3 m in diameter. The gap between the permanent steel sleeve and the steel container facilitates relatively easy container removal (i.e., reversibility).

ONDRAF/NIRAS-type variant of the horizontal borehole placement method

The ONDRAF/NIRAS approach, another variant of the horizontal borehole placement method, comprises super-containers (i.e., a waste container in a carbon steel overpack surrounded by a Portland-cement-based buffer within a stainless steel outer vessel) placed in horizontal boreholes (about 2 m in diameter) that are lined with concrete wedge blocks to provide structural stability in the Belgian Boom clay (a soft clay).

4.2.1 Technical Feasibility

The KBS-3H-type variant of the horizontal borehole placement method is an alternative used-fuel-container placement method being developed by SKB and Posiva for their deep geological repository in crystalline rock. This placement method uses a “super-container package” that includes the used-fuel container surrounded by the highly compacted bentonite buffer material and a protective outer metal sheath. In a Canadian context, this placement method should be applicable for a deep geological repository in Canadian crystalline rock but this would have to be confirmed.

The ANDRA-type variant of the horizontal borehole placement method is developed specifically to address the issue of reversibility (i.e., relatively easy retrieval) in a deep geological repository placed in a soft sedimentary rock formation. To this end, it uses a tunnel liner and has a gap between the permanent steel sleeve and the steel container that would facilitate relatively easy container removal, but would also prevent contact of the highly compacted bentonite buffer with the container surface. In order to consider this placement method for application in crystalline rock, it would be necessary to: modify the placement concept to remove the borehole liner, which would be an unnecessary cost and complexity; and assess the potential for microbial activity near the container since the bentonite buffer would not be in close contact with the container.

The ONDRAF/NIRAS-type variant of the horizontal borehole placement method is being developed for a soft sedimentary rock application. The method uses a supercontainer package comprising a concrete buffer and an overpack around the waste container and segmented concrete liners to support the placement boreholes. As the effectiveness of the concrete buffer and supercontainer assembly in providing containment in Canadian crystalline rock conditions is unknown, the ONDRAF/NIRAS-type variant of the horizontal borehole placement method would require further study and analyses.

Conventional or tested technologies can be applied for excavation of placement rooms/tunnels and placement boreholes, and for placing the container and sealing materials in Canadian crystalline rock. SKB, Posiva and ANDRA have also demonstrated in non-radioactive environments many of these technologies in crystalline or sedimentary rock. Conventional mining and civil engineering in Canada use methods that could be applied to these placement methods.

4.2.2 Siting

The stability of the placement borehole or tunnel would depend on site-specific conditions (i.e., rock mass quality and strength, in-situ stress) and the size and shape of these openings. The KBS-3H horizontal borehole placement method is less tolerant of rock spalling at the placement borehole perimeter than the in-floor borehole or the horizontal tunnel placement methods. Relatively precise borehole straightness, dimensions and shape are required to facilitate the placement of large super-container packages and spacer assemblies. It would be difficult to place gap fill in small perimeter gaps over long distances in the long horizontal boreholes. In order to apply this placement method in Canada, it would be prudent to demonstrate that long and straight horizontal boreholes can be effectively excavated and appropriate sealing systems applied under Canadian repository conditions.

The ANDRA-type variant and the ONDRAF/NIRAS-type variant of the horizontal borehole placement method would likely require a lower tolerance on placement borehole straightness, diameter and ovality if applied in crystalline rock because they include liners that would be placed in the borehole. The liners would provide the straightness and ovality required to apply the placement method. The use of the liners with these two horizontal borehole placement method variants would increase the materials and effort necessary to apply the concept in hypothetical crystalline rock assumed in this assessment as they would not be needed for rock stability.

If the rate of water seepage into a horizontal borehole placement area is significant, the seeping water could affect the placement and thus the as-placed properties of sealing-materials. This could impact the performance of the placement room sealing system and therefore the repository. This issue would be important for KBS-3H-type variant of the horizontal borehole placement method in crystalline rock with water-bearing fractures. Practical and effective methods would need to be developed to deal with the issues related to water seepage. The ANDRA-type variant and ONDRAF/NIRAS-type variant of the horizontal borehole placement method could be less affected if a borehole liner is used as the liner could direct the seepage away from the in-borehole sealing system.

4.2.3 Safety

The public and occupational safety of a deep geological repository concept using the in-floor borehole placement method in crystalline rock during the preclosure period has been analyzed by Grondin et al. (1994). The occupational risks from preclosure repository operations were shown to be within regulatory limits and guidelines or readily mitigated to be within the regulatory limits and guidelines. It is expected that an appropriate level of the public and occupational safety would be achieved for a repository using the horizontal borehole placement method by careful design, despite the fact that the complexity of operations, extent of working in confined space and the size of facility are not the same for each of the variants of this placement methods.

The Canadian technical program has conducted a postclosure safety assessment of deep geological repository in a Canadian crystalline geosphere using horizontal borehole placement method similar to the KBS-3H method (Garisto et al. 2005). This postclosure safety assessment found that the estimated dose rates to the public were well below the regulatory limit for the assumed site.

A feature of the KBS-3H-type variant of the horizontal borehole placement method using the super-container package design is that the high density bentonite buffer in close contact with the used fuel container would suppress the microbial activity at or near the container surface and thus the potential for microbially-influenced corrosion of the containers.

The KBS-3H-type variant of the horizontal borehole placement method may have a steel sleeve surrounding the bentonite buffer that will generate hydrogen gas from corrosion. The potential adverse effect of hydrogen gas generation and its build-up on the integrity of the buffer and surrounding host rock is a safety issue that will need further study and assessment. The potential adverse effect of iron-bentonite interaction on the properties and performance of the bentonite buffer also need to be evaluated. SKB and Posiva have proposed the replacement of the steel components with titanium components as a potential solution to eliminate the adverse effect from hydrogen gas generation and iron/bentonite interaction (SKB 2008).

A potential issue with the ANDRA-type variant of the horizontal borehole placement method in a Canadian deep geological repository in crystalline rock is the presence in the sealing-system design of gaps. There is a gap between the permanent steel sleeve and the container that would prevent contact between the buffer and the container. This could prevent the buffer material from suppressing microbial activity and facilitate the development of microbially-influenced corrosion on the container surface. There will also be a gap between the tunnel liner, if used, and the rock, which would eventually close due to the creep in soft sedimentary rock but will remain open in crystalline rock or hard sedimentary rock. This gap could be a preferential path for radionuclide transfer and the potential effect on long-term safety would have to be determined.

A potential issue with the ONDRAF/NIRAS-type variant of the horizontal borehole placement method is the uncertainty regarding the effectiveness of concrete as a buffer material in a Canadian crystalline rock. Further study and assessment would be required to address this issue.

4.2.4 Monitoring

The monitoring program for a deep geological repository in any host media could be developed in the framework proposed by Simmons (2006). The ability to design a system to meet monitoring requirements for a deep geological repository using the in-floor borehole, the horizontal borehole, or the horizontal tunnel placement methods are expected to be similar.

4.2.5 Retrieval

For these variants of the horizontal borehole placement method, the container retrieval process would require the removal of all containers up to and including the container(s) of interest.

For the KBS-3H-type variant of the horizontal borehole placement method, SKB and Posiva have demonstrated that it is possible to readily recover a deposited super-container package from the horizontal borehole by using the same container placement equipment during the period that the buffer has not yet absorbed water (i.e., reverse operation) (SKB 2008). SKB and Posiva have also proposed a step-wise procedure for retrieving a deposited super-container package from a sealed horizontal borehole after the buffer has absorbed water (SKB 2008). They have concluded that the super-container package can be retrieved after installation. However, it would be prudent to demonstrate that the techniques are appropriate for a Canadian crystalline rock conditions.

The ANDRA-type horizontal borehole placement method is developed specifically to allow the retrieval of placed containers (i.e., reversibility).

The SAFIR 2 report (ONDRAF/NIRAS 2002) states that the ONDRAF/NIRAS-type horizontal borehole placement method provides for possible retrieval after repository sealing and closure.

4.3 HORIZONTAL TUNNEL PLACEMENT METHOD

The two variants of the horizontal tunnel placement method considered in this report are summarized below.

CTECH-type variant of the horizontal tunnel placement method

The CTECH-type variant of the horizontal tunnel placement method was used in a Canadian crystalline rock repository design concept. The CTECH-type variant of the horizontal tunnel placement method includes 324-used-fuel bundles in a “super-container-type” assembly, 3.6-million-bundle used fuel inventory, a placement tunnel sealing system that includes highly compacted bentonite buffer within the “super-container-type” assembly, and a block structure of dense backfill and a particulate light backfill that supports and surrounds the super-container-type assemblies. In this study, two “super-container-type” assemblies are placed abreast along the length of a placement tunnel, spaced to meet the thermal and mechanical design criteria.

NAGRA-type variant of the horizontal tunnel placement method

In the NAGRA-type variant of the horizontal tunnel placement method, each 150-mm-thick carbon steel container of spent fuel, 1.05-m in diameter and 4.6-m-long and with a mass of 26 Mg, would be placed on top of a highly compacted bentonite pedestal inside 2.5-m-diameter horizontal tunnels. The spacing between containers would be 3 m. The remaining voids around the container in the placement tunnel would be backfilled with granular bentonite material that would have a moisture content of about 2%, and would comprise 80% by volume very dense pellets (about 2.1 to 2.2 g/cm^3) and 20% bentonite powder. Upon placement, NAGRA expects the granular material to have an average dry density of 1.5 g/cm^3. When a placement tunnel is filled with the intended number of containers, the tunnel is sealed at the ends.

4.3.1 Technical Feasibility

CTECH-type variant of the horizontal tunnel placement method proposes a relatively complex sealing system in the placement tunnel that consists of a complex array of sealing components including shaped-blocks of highly-compacted bentonite, 50/50 bentonite/sand, and dense backfill, pneumatically placed light backfill material, and low alkalinity concrete. The elements of the sealing system placed before the super-container-type assemblies could shift before the super-container-type assemblies and block placement is completed. This would make the placement of the final buffer blocks difficult and could result in an incomplete or inadequate sealing system. In order to establish that this variant of the horizontal tunnel placement method is technically viable, the method of placing containers and the sealing system blocks would need to be demonstrated.

The NAGRA-type variant of horizontal tunnel placement method has some practical advantages over the CTECH-type variant of the placement method. It has a simpler placement tunnel sealing system comprising highly compacted bentonite pedestals and a size-graded highly compacted bentonite particulate buffer. By using HCB pellets and fines to fill the voids in the placement room following placement of containers, the requirement on dimensional and straightness control of the excavation of the rooms is less critical than with the KBS-3H horizontal borehole placement method. This implies that a bored tunnel may not be necessary for this placement method and the relatively simple drill and blast method may be used for excavating the horizontal placement tunnels. However, this would have to be demonstrated.

Conventional technologies can be applied for excavation of tunnels, placement of the HCB pedestal, the container and HCB pellets/fines. NAGRA has demonstrated many of these technologies in hard sedimentary rock. Conventional mining and civil engineering activities in Canada use methods that could be applied for application of the NAGRA-type variant of the horizontal tunnel placement method in Canadian crystalline rock. Similarly, conventional methods could be applied to the excavation of placement tunnels for the CTECH-type variant of the horizontal tunnel placement method.

For application in Canadian crystalline rock, there are potential issues with both variants of the horizontal tunnel placement method. The CTECH-type variant has a complex sealing system that has not been shown to be practical. In the NAGRA-type variant, the composition, the placement method and the as-placed density of the particulate buffer material appropriate for Canadian crystalline rock conditions would need to be developed and demonstrated.

4.3.2 Siting

The CTECH-type variant and the NAGRA-type variant of the horizontal tunnel placement method are the placement methods that are most tolerant of rock breakout since the placement tunnel cross section can be varied, subject to the minimum geometric limits imposed by operating equipment, to accommodate high in-situ rock stresses. With the CTECH-type variant, the light backfill used to complete the room backfilling to the excavation perimeter can adapt to irregular opening boundaries. With the NAGRA-type variant, the bentonite pellets and fines used as buffer to fill the placement tunnel around the placed containers can adapt to irregular openings. However, it would be prudent to demonstrate the effective placement of the light backfill and the particulate bentonite buffer.

Both the CTECH-type variant and the NAGRA-type variant of the horizontal tunnel placement method will be susceptible to water seepage into the placement area from a water-bearing fracture. The effect of water seepage into the placement area on container placement and buffer integrity must be assessed. Practicable methods for either reducing the water seepage rate to be below an acceptable water seepage rate or to otherwise mitigate the effects of water seepage would need to be developed and demonstrated.

4.3.3 Safety

CTECH-type variant of the horizontal tunnel placement method proposes a complex sealing system. The elements of the sealing system, placed before the super-container-type assemblies, could shift before the super-container-type assemblies and block placement is completed. This would make the placement of the final buffer blocks difficult and could result in an incomplete or inadequate sealing system. The ability of the sealing system to remain stable, to be placed as designed and to provide adequate long-term safety would need to be demonstrated.

Based on NWMO’s technical program, an important aspect of postclosure safety is the suppression of microbial activity near and the potential for microbially influenced corrosion of the used-fuel container. NWMO’s microbial experiments have indicated that for a low-salinity environment (e.g., < 60 g NaCl/L), as would be expected in some crystalline rock formations, a bentonite dry density of ≥1.6 g/cm^3 would be required to suppress microbial activity and microbially influenced corrosion of the containers under aerobic conditions (Stroes-Gascoyne et al. 2006). SKB has conducted microbial experiments that show the activity of the sulphate reducing bacteria is also greatly suppressed in bentonite samples with a saturated density of ≥1.8 g/cm^3 (Pedersen et al. 2000).

For the NAGRA-type variant of the horizontal tunnel placement method, the particulate buffer consists of 80% bentonite highly compacted pellets and 20% bentonite powder. The as-placed bentonite pellet and powder are expected by NAGRA to have an average dry density of 1.5 g/cm^3 (Johnson and King 2003). This is less than the as-placed density of 1.6 g/cm^3 required to inhibit microbial activity and the potential for microbially influenced corrosion of a copper used-fuel container (Stroes-Gascoyne and Hamon. 2008). Further development of the composition and placement of the particulate buffer material would be required for application of the NAGRA-type variant of the horizontal tunnel placement method in Canadian crystalline rock conditions.

Although no postclosure safety assessment has been performed on the horizontal tunnel placement method in a Canadian context, it is anticipated satisfactory postclosure safety can be achieved in this placement method, subject to the improvements to achieve the necessary as-placed density in the sealing system.

4.3.4 Monitoring

The monitoring program for a deep geological repository in any host media could be developed in the framework proposed by Simmons (2006). The ability to design a system to meet monitoring requirements for a deep geological repository using the in-floor borehole, the horizontal borehole, or the horizontal tunnel placement methods are expected to be similar.

4.3.5 Retrieval

Retrieval of containers from the CTECH-type variant of the horizontal tunnel placement method is described in CTECH (2002). The method depends on a very precise removal of the sealing material below each container as a support dolly is moved under the container. It would be prudent to demonstrate the feasibility of container retrieval from the CTECH-type variant of this placement method.

Retrieval of containers during the operational and postclosure phases from the NAGRA-type variant of the horizontal tunnel placement method is considered to be possible by NAGRA. Johnson and King (2003) indicate that excavation into the bentonite to retrieve containers is not intrinsically difficult, thus retrievability is considered possible as long as containers remain structurally sound, which implies a period of easy retrievability of the order of at least some hundreds of years.

5. EVALUATION OF CONTAINER PLACEMENT METHODS FOR APPLICATION IN HARD SEDIMENTARY ROCK

5.1 IN-FLOOR BOREHOLE PLACEMENT METHOD

5.1.1 Technical Feasibility

As mentioned in Section 4.1.1, the in-floor borehole placement method and associated technologies are well developed for deep geological repository concepts in crystalline rock. It is anticipated that most of the technologies, including excavation technologies, backfilling technologies, and placement technologies for the containers, are transferable to self-supporting hard sedimentary rock.

It is expected that practicable repository layouts can be achieved in hard sedimentary rock using the in-floor borehole placement method. However, this would need to be confirmed by modelling under anticipated conditions in hard sedimentary rock in Canada.

5.1.2 Siting

The employment of the in-floor borehole placement method will increase the vertical thickness of the repository and use more of the vertical depth of the host sedimentary formation than the horizontal placement methods thereby reducing the thickness of the diffusive barrier above and/or below the repository. Therefore, the in-floor borehole placement method could be suitable for a DGR in a hard sedimentary host rock formation with appropriate thickness.

Modelling and excavation trials would confirm that stable in-floor boreholes without excessive rock breakout on the borehole wall near the intersection between the borehole and the tunnel floor can be constructed under anticipated hard sedimentary rock conditions in Canada.

For hard sedimentary rock with water-bearing fractures, the issue related to water seepage into the placement rooms or in-floor boreholes would need to be assessed. The in-floor borehole method is more tolerant to water seepage than the horizontal borehole or horizontal tunnel placement methods, because either the seepage area can be more easily isolated from container placement activities or, if the seepage is into a placement borehole, the borehole can be sealed without a used-fuel container.

5.1.3 Safety

Safety assessment studies using site-specific and repository-design-specific data will be required to determine whether the extent of disturbance of the diffusive layer of the sedimentary rock formation above and below the repository excavations imposed by the geometry of the in-floor borehole placement method will impact the long-term safety.

NMWO’s microbial experiments under aerobic conditions have indicated that high groundwater and porewater salinity of ≥ 60 g NaCl/L will suppress microbial activity and the potential for microbially-influenced corrosion of the containers (Stroes-Gascoyne and Hamon 2008). The groundwater salinity in potentially suitable hard sedimentary rock in Canada is expected to be greater than 100 g NaCl/L, which is more than adequate to suppress the microbial activity. As described in Section 4.1.3, the highly compacted bentonite surrounding the container in the in-floor borehole rings and discs will also suppress the microbial activity and microbially-influenced corrosion of the containers. Therefore, it is expected that microbially-influenced corrosion will not affect the long-term integrity of the containers and postclosure safety of the repository in hard sedimentary rock.

The hydrogen gas generation issue in sedimentary rock would need to be addressed if used-fuel containers with a steel corrosion barrier rather than copper corrosion barrier are to be used in the in-floor borehole placement method since the placement method does not include other ferrous components.

Preliminary carbon steel corrosion assessments suggest that, based on a combination of uniform and pitting corrosion, the range of corrosion progression will be 9-34 mm after 10,000 years and 34-175 mm after 100,000 years (King 2007). It is expected that a steel container would still have sufficient remaining wall thickness and mechanical strength to avoid through-wall penetration for a period of more than 10,000 years after it is placed in a repository in sedimentary rock. This analysis suggests, therefore, that carbon steel containers can provide containment of used fuel for substantial periods of time in a deep geological repository in sedimentary rock. Other corrosion processes such as hydrogen-related effects, stress corrosion cracking, microbially-influenced corrosion, preferred weld corrosion and dry air oxidation are excluded based on the assumptions that either environment will not support these processes or that these processes can be avoided by proper container design and fabrication processes (King 2007).

5.1.4 Monitoring

The experience in Canada with instrumentation for monitoring in hard and soft sedimentary rock formations is much more limited than it is for monitoring in hard crystalline rock media. The availability of instruments suitable for long-term monitoring in a sedimentary rock environment is limited although sensors to measure most of the parameters have been developed and used in short-term experiments and demonstrations in surface and underground research laboratories in Canada and abroad. In hard sedimentary rock, the monitoring requirements for a deep geological repository using the in-floor borehole placement method are expected to be achievable. There is expanding international experience with applying instrumentation to in situ investigations and demonstrations in both hard and soft sedimentary rock formations. The monitoring program for a deep geological repository in any host media could be developed in the framework proposed by Simmons (2006).

High groundwater salinity is expected for both hard and soft sedimentary rock in Canada. There is a need to develop monitoring equipment that can maintain its integrity and perform for long periods in high-salinity environments.

5.1.5 Retrieval

As discussed in Section 4.1.5, some aspects of container retrieval from in-floor borehole placement under non-radioactive conditions after a short placement time have been successfully demonstrated in hard crystalline rock at SKB's Äspö HRL in Sweden. The retrieval of containers from an in-floor borehole placement in hard sedimentary rock is expected to be similar to retrieving containers from boreholes in a crystalline rock formation.

5.2 HORIZONTAL BOREHOLE PLACEMENT METHOD

5.2.1 Technical Feasibility

a) KBS-3H-type Variant of the Horizontal Placement Method

As discussed in Section 4.2.1, the KBS-3H-type variant of the horizontal borehole placement method has been developed and many aspects have been demonstrated for a DGR design in crystalline rock by SKB and Posiva. This placement method is considered by the authors to be technically feasible for a deep geological repository design in hard sedimentary rock. Useful information on repository design and the fabrication and placement of the super-container package will be available in the work done by SKB and Posiva. However, this information, methods and equipment would have to be confirmed as being applicable in hard sedimentary rock in Canada.

As mentioned previously, the horizontal borehole placement method imposes stringent requirements on controlling the borehole straightness and dimensions, and on limiting the extent of rock breakout. It would be prudent to demonstrate that acceptable long horizontal boreholes to facilitate the placement of super-container packages can be excavated in hard sedimentary rock in Canada.

b) ANDRA-type Variant of the Horizontal Borehole Placement Method

As discussed Section 4.2.1, the ANDRA-type variant of the horizontal borehole placement method is developed specifically to address the issue of reversibility in a soft sedimentary rock. A tunnel liner is used to maintain borehole openings in the soft sedimentary rock. This method is likely to be technically feasible for a DGR design in hard sedimentary rock.

c) ONDRAF/NIRAS-type Variant of the Horizontal Borehole Placement Method

The ONDRAF/NIRAS-type variant of the horizontal borehole placement method is specifically for DGR design in soft sedimentary rock. A concrete liner is used to maintain the borehole opening in the soft sedimentary rock. A concrete buffer is used as part of the supercontainer package. This method may be potentially applicable for a DGR design in hard sedimentary rock in Canada. However, because of the significant differences in the supercontainer and sealing system designs (i.e., the use of concrete as a buffer), it would be prudent to assess the impact of these differences on repository safety in a Canadian hard sedimentary rock.

5.2.2 Siting

a) KBS-3H-type Variant of the Horizontal Placement Method

There is a need to demonstrate that long horizontal boreholes to tolerances that would facilitate the placement of super-container packages can be excavated in hard sedimentary rock in Canada (see Section 5.2.1(a)).

If the rate of water seepage into the placement area of a KBS-3H-type variant of the horizontal borehole placement method is significant; the seeping water could affect the placement and the as-placed properties of the sealing materials. This could impact the performance of the placement borehole sealing system and therefore the repository. Practical and effective methods would be needed to deal with the issues related to water seepage.

b) ANDRA-type Variant and ONDRAF/NIRAS-type Variant of the Horizontal Borehole Placement Method

The potential siting constraints for applying these two variants of the horizontal borehole placement method are discussed in Section 4.2.2 for crystalline rock application and are also applicable for applications in hard sedimentary rock.

The ANDRA-type and ONDRAF/NIRAS-type variants of the horizontal borehole placement method would be less affected by water seepage than the KBS-3H-type variant because they each include a borehole liner that would direct the seepage away from the in-borehole sealing system.

5.2.3 Safety

a) KBS-3H-type Variant of the Horizontal Placement Method

As discussed in Section 4.2.2, the container is surrounded by highly compacted bentonite buffer inside the super-container package. It is anticipated that the high salinity of groundwater and porewater in hard sedimentary rock in Canada (see Section 5.1.3) and the characteristics of the highly compacted bentonite buffer will suppress microbial activity and the potential for microbially-influenced corrosion of the containers.

An issue to be considered is the effect of hydrogen gas generation and pressure build-up within the repository due to anaerobic corrosion of the steel components of this variant, including steel used-fuel containers if this container design is used, particularly for sedimentary rock with low strength and low gas permeability. It would be prudent to assess the potential impact of the hydrogen gas generation on the integrity of the sealing system and host rock under Canadian sedimentary rock conditions.

Another issue is the potential adverse effect of iron-bentonite interaction on the properties and performance of the bentonite buffer, which might be caused by interaction between the buffer and the steel components, and the steel containers, if used. It would be prudent to assess the significance of this effect on sealing performance and repository safety.

Should the issues related to hydrogen gas or the iron-bentonite interaction be significant in the context of repository performance, the effects could be mitigated by using copper containers and fabricating the larger steel components of the super-container package from another material, such as titanium.

The effect of water seeping at too high a rate from water-bearing fractures in hard sedimentary rock into the sealing materials placement areas and the effect of this water on the as-placed characteristics of the sealing materials will need to be addressed either by developing and demonstrating mitigation methods or by confirming by safety assessment the long-term safety of the repository containing altered sealing materials.

b) ANDRA-type Variant of the Horizontal Borehole Placement Method

As discussed in Section 4.2.3, a gap will exist between the tunnel liner and the rock. The gap will eventually be closed in ANDRA's soft sedimentary rock due to rock creep. However, this gap will remain open since there is assumed to be no rock creep in hard sedimentary rock and it could be a preferential path for radionuclide transfer. Safety assessment studies will be required to determine if this would affect the long-term safety of the repository.

As discussed in Section 4.2.3, the container will be placed inside the permanent steel sleeves. There will be an air gap between the container and the steel sleeve, which will not be backfilled with bentonite buffer. The effectiveness of highly saline groundwater in hard sedimentary rock (i.e., without the presence of bentonite buffer) on suppressing microbial activity and microbially-influenced corrosion of the containers would need to be confirmed.

As discussed in Section 2.2.2, the ANDRA-type variant consists of steel components such as the steel borehole liner and the permanent steel sleeve. If steel containers are to be used in this variant, it would be prudent to assess the effect of hydrogen gas generation and pressure build-up resulting from the anaerobic corrosion of the steel components and the steel containers on the integrity of the sealing system and host rock under Canadian hard sedimentary rock conditions.

The potential adverse effect of iron-bentonite interaction on the properties and performance of the bentonite buffer would need to be assessed. It would be prudent to assess the significance of this effect on repository performance and safety.

c) ONDRAF/NIRAS-type Variant of the Horizontal Borehole Placement Method

As discussed in Section 4.2.3, the container is expected to be surrounded by a concrete buffer inside the super-container package. The effectiveness of the concrete buffer on long-term safety of the repository and long-term integrity of the container under highly saline sedimentary rock environments would need to be assessed. Because of the significant differences in the supercontainer design and sealing system used, the long-term safety of this placement method for hard sedimentary rock in Canada would need to be assessed.

5.2.4 Monitoring

See Section 5.1.4.

5.2.5 Retrieval

The discussion on retrieval of used fuel from all three placement methods in Section 4.2.5 is also applicable for DGR design in hard sedimentary rock.

5.3 HORIZONTAL TUNNEL PLACEMENT METHOD (NAGRA-type Variant)

In this Section, only the NAGRA-type variant of the horizontal tunnel placement method will be discussed. The CTECH-type variant of the horizontal tunnel placement method will not be considered for any geological media, including hard sedimentary rock, based on the issues discussed in Section 4.

5.3.1 Technical Feasibility

The horizontal tunnel placement method with particulate bentonite backfilling has been developed by NAGRA for a repository in hard sedimentary rock (i.e., Opalinus Clay). It is considered as a technically viable placement method for the design of a Canadian geological repository in hard sedimentary rock.

5.3.2 Siting

Because highly compacted bentonite pellets are used as buffer material to fill the remaining voids in the placement tunnel following container placement, the requirement on dimensional and straightness control on the excavation of the tunnels is less critical than with other placement methods. In comparison with the horizontal borehole placement method, the horizontal tunnel placement can tolerate a wider range dimensional variations, rock breakouts, rock properties and stresses.

5.3.3 Safety

NAGRA expects that it is possible to achieve an average dry density of 1.5 g/cm^3 for the particulate bentonite buffer, which is below the bentonite dry density of ≥ 1.6 g/cm^3 required for suppressing the microbial activity and microbially influenced corrosion of the containers (see Section 4.1.3). As discussed in Section 5.1.3, NWMO’s microbial experiments have indicated that a high groundwater and porewater salinity of ≥ 60 g NaCl/L is capable of suppressing microbial activity at or near the container surface (Stroes-Gascoyne and Hamon 2008). It is expected that microbial activity and microbially influenced corrosion will be suppressed by the groundwater and porewater salinity of >100 g NaCl/L, which is anticipated for hard and soft sedimentary rock in Canada.

As discussed in Section 5.2.3, the effect of the generation of hydrogen gas and associated pressure-build-up due to anaerobic corrosion of steel components and steel containers on sealing system performance and repository safety would need to be assessed. The potential effect of iron-bentonite interaction (i.e., between the steel components and steel containers, if used, and the bentonite buffer) on the properties and performance of the bentonite buffer would need to be evaluated.

The effect of water seeping at high rates from water-bearing fractures in hard sedimentary rock into the sealing materials placement areas and its effect on the as-placed characteristics of the sealing materials would need to be addressed. Either mitigation methods should be developed and demonstrated or safety assessments should be done to confirm that the long-term safety of the repository is not affected by the altered properties of the sealing materials.

5.3.4 Monitoring

See discussion in Section 5.1.3.

5.3.5 Retrieval

Although NAGRA states that it is feasible to retrieve from their variant of horizontal tunnel placement, there is a need to demonstrate that retrieval is technically viability and develop confidence that potentially suitable techniques and equipment can be developed (see Section 4.3.5).

6. EVALUATION OF CONTAINER PLACEMENT METHODS FOR SOFT SEDIMENTARY ROCK

6.1 IN-FLOOR BOREHOLE PLACEMENT METHOD

6.1.1 Technical Feasibility

For soft sedimentary rock, tunnel, placement room and borehole liners will be required to manage the rock mass creep into the excavations and to prevent excessive rock failure. The practicality and cost of committing the material and time to apply borehole liners and placement-room liners would need to be assessed in designing a repository using the in-floor borehole placement method in soft sedimentary rock.

6.1.2 Siting

As discussed in Section 5.1.2 there would be a reduction of diffusive barrier thickness of the host rock above and below the repository from using the in-floor borehole placement. This is an issue that may become important if the repository is to be located in a relatively thin rock formation and there is a desire to maximize the diffusive barrier of undisturbed host rock above and below the repository.

6.1.3 Safety

Section 5.1.3 discusses issues related to microbial activity/microbially influenced corrosion, hydrogen generation and steel/bentonite interaction. These issues are also relevant to a deep geological repository in soft sedimentary rock.

6.1.4 Monitoring

Section 5.1.4 discusses issues related to the availability of monitoring instrumentation for use in sedimentary rock and the need to address instrument performance in high salinity groundwater. In soft sedimentary rock the issue of instrument design, performance and longevity in creeping rock must also be addressed.

6.1.5 Retrieval

Section 4.1.5 discusses the experience for container retrieval for an in-floor borehole placement method in crystalline rock. The crystalline rock experience is based on having a hard stable borehole boundary that is not significantly affected by processes used in loosening the container from the borehole. This will not be the case in soft sedimentary rock and therefore the technologies for container retrieval from in-floor borehole placement in soft sedimentary rock where the tunnel and borehole perimeters are not stable must be developed.

6.2 HORIZONTAL BOREHOLE PLACEMENT METHOD

6.2.1 Technical Feasibility

a) KBS-3H-type Variant of the Horizontal Borehole Placement Method

As described previously, this variant of the horizontal borehole placement method is being developed specially for crystalline rock by SKB and Posiva. It is expected that this variant could be adapted for application in soft sedimentary rock by the addition of tunnel liners and borehole liners. In this case, the placement of the super-container packages will need to rely on the straightness and dimensional control of the liner. Rock breakout after liner installation would not create any problem during placement operation of the super-container packages.

b) ANDRA-type Variant of the Horizontal Borehole Placement Method

This variant of the horizontal borehole placement method is specifically developed for soft sedimentary rock and would likely be applicable for soft sedimentary rock in Canada.

c) ONDRAS/NIRAS Horizontal Borehole Placement Method

This placement method is specifically developed for soft sedimentary rock and would likely be applicable for soft sedimentary rock in Canada. Because of the significant differences in the supercontainer and sealing systems designs, it would be prudent to assess the long-term safety of this placement method under Canadian soft sedimentary rock conditions.

6.2.2 Siting

a) KBS-3H-type Variant of the Horizontal Borehole Placement Method

With the use of tunnel and borehole liners, the requirements for borehole straightness, dimensional control and rock breakout are expected to be more relaxed. It is expected that this placement method can be applied in soft sedimentary rock. However, the borehole liner would have to support the loads imposed by the creeping host rock.

b) ANDRA-type Variant and ONDRAF/NIRAS-type Variant of the Horizontal Borehole Placement Methods

These two placement methods are specifically designed for soft sedimentary rock. No specific site constraints have been identified.

6.2.3 Safety

a) KBS-3H-type Variant of the Horizontal Borehole Placement Method

Groundwater salinity of ≥100 g NaCl/L is expected for soft sedimentary rock in Canada, which will be significantly greater that the minimum salinity of 60 g NaCl /L required to suppress microbial activity and microbially-influenced corrosion of containers (see Section 5.2.3).

The impact of hydrogen gas generation and associated pressure build-up from anaerobic corrosion of the steel components and steel container on the long-term safety of a deep geological repository in soft sedimentary rock would need to be assessed.

b) ANDRA-type Variant of the Horizontal Borehole Placement Method

As discussed in Section 5.2.3, the effectiveness of the highly saline groundwater in sedimentary rock environments (i.e., without the presence of highly compacted bentonite buffer) on suppressing microbial activity and microbially-influenced corrosion of containers would need to be confirmed.

As discussed in Section 5.2.3, the effect of hydrogen gas generation and pressure build-up resulting from the anaerobic corrosion of the steel components and the steel containers on the integrity of the sealing system and host rock would need to be addressed under Canadian soft sedimentary rock conditions.

It would also be prudent to consider the potential adverse effect of iron-bentonite interaction on the properties and performance of the bentonite buffer, and the significance of this effect on sealing system performance and repository safety under Canadian soft sedimentary rock conditions.

c) ONDRAF/NIRAS-type Variant of the Horizontal Borehole Placement Method

Section 5.2.3 discusses the issue of the uncertainties regarding the use of concrete as a buffer material surrounding the container.

6.2.4 Monitoring

Section 5.1.4 discusses monitoring in a DGR in hard or soft sedimentary rock.

6.2.5 Retrieval

Section 4.2.5 discusses the experience for container retrieval from a KBS-3H horizontal borehole in crystalline rock (SKB 2008). The crystalline rock experience is based on having a hard stable borehole boundary that is not significantly affected by processes used in loosening the container from the borehole. This will not be the case in soft sedimentary rock and therefore the technologies for container retrieval from horizontal borehole placement in soft sedimentary rock, where the tunnel and borehole perimeters, are not stable must be developed.

The ANDRA-type horizontal borehole placement method is developed specifically to allow the retrieval of placed containers (i.e., reversibility) in soft sedimentary rock.

As discussed in Section 4.2.5, the SAFIR 2 report (ONDRAF/NIRAS 2002) states that the ONDRAF/NIRAS-type horizontal borehole placement method provides for possible retrieval after repository sealing and closure.

6.3 HORIZONTAL TUNNEL PLACEMENT METHOD (NAGRA-type Variant)

The NAGRA-type variant of the horizontal tunnel placement method is the only variant to be discussed in this section. The CTECH-type variant of the horizontal tunnel placement method will not be considered for any geological media, including soft sedimentary rock, based on the issues discussed in Section 4.

6.3.1 Technical Feasibility

Although the NAGRA-type variant of the horizontal placement method is developed primarily for hard sedimentary rock, this placement method can be potentially applied for DGR design in soft sedimentary rock with the addition of a tunnel liner to control rock creep.

6.3.2 Siting

The rock properties and stresses at a site are a factor in the excavation of stable tunnels to the necessary specifications. The use of tunnel liners in soft sedimentary rock mitigates this factor.

6.3.3 Safety

Section 5.3.2 discusses the issue of suppressing microbial activity and the potential for microbially-influenced corrosion. The high salinity expected in soft sedimentary rock in Canada should suppress microbial activity in the bentonite buffer at or near the container surface and will suppress the microbially influenced corrosion of the containers.

As discussed in Section 5.3.3, the effect of the generation of hydrogen gas and associated pressure-build-up due to anaerobic corrosion of steel components and steel containers, if used, on repository performance and safety in soft sedimentary rock would need to be assessed. The potential effect of iron-bentonite interaction (i.e., interactions between the steel components/steel containers, if used, and the bentonite buffer) on the properties and performance of the bentonite buffer would need to be evaluated.

6.3.4 Monitoring

See discussion in Section 5.1.4.

6.3.5 Retrieval

Section 4.1.5 discusses the experience for container retrieval for an in-floor borehole placement method in crystalline rock. The crystalline rock experience is based on having a hard stable borehole boundary that is not significantly affected by processes used in loosening the container from the borehole. This would not be the case in soft sedimentary rock and therefore the technologies for container retrieval from horizontal tunnel placement in soft sedimentary rock would need to be developed.

7. CONCLUSIONS

Three generic used fuel container placement methods for a deep geological repository have been evaluated in a qualitative manner based on technical feasibility, safety, siting, monitoring and retrieval for application in crystalline rock, hard sedimentary rock and soft sedimentary rock. The container placement methods were derived from a review of repository concepts being developed by national radioactive waste management organizations. Two of the container placement methods have variants, which depend in part on national program designs and site specific conditions.

7.1 In-floor Borehole Placement Method

The in-floor borehole placement method has been well developed and demonstrated for a deep geological repository in crystalline rock. It is the reference container placement method for crystalline rock in Sweden and Finland and there are only minor variations in design amongst the national programs. The in-floor borehole placement method could also be applied to hard sedimentary rock, but may not be applicable to soft sedimentary rock without significant ground support and other engineering modifications.

7.2 Horizontal Borehole Placement Method

7.2.1 KBS-3H-type Variant of the Horizontal Borehole Placement Method

The KBS-3H-type variant of the horizontal borehole placement method is applicable in a crystalline rock environment. SKB and Posiva have developed technologies to excavate long and straight boreholes with tight dimensional tolerances, fabricate the super-container packages and place the super-container package and sealing materials into long, horizontal boreholes.

The KBS-3H-type variant of the horizontal borehole placement method would likely be applicable in hard sedimentary rock but may be unsuitable for soft sedimentary rock without the addition of placement room and borehole liners for ground control.

7.2.2 ANDRA-type Variant of the Horizontal Borehole Placement Method

The ANDRA-type variant of the horizontal borehole placement method has been developed for soft sedimentary rock. A borehole liner is used to control rock creep. The waste containers are placed inside a permanent steel sleeve. Bentonite buffer is placed outside the permanent sleeve to allow easy retrieval of placed containers (i.e., reversibility). This leaves a gap between the container and the steel sleeve with no bentonite buffer. The potential for microbial activity near the container and the potential for microbially-influenced corrosion of the container would need to be assessed for application in crystalline rock, hard and soft sedimentary rock.

For self-supporting crystalline rock and hard sedimentary rock, the borehole liner would not be required for ground control. The ANDRA-type variant with a borehole liner would be feasible but is not considered to be a practical placement method for crystalline and hard sedimentary rock. The practicality of applying this placement method without a borehole liner for crystalline rock and hard sedimentary rock would need to be assessed.

Since both crystalline rock and hard sedimentary rock are not expected to creep, the gap between the borehole liner and the rock would remain open. The potential impact of this open gap on the long-term repository safety would need to be addressed.

7.2.3 ONDRAF/NIRAS -type Variant of the Horizontal Borehole Placement Method

The ONDRAF/NIRAS-type variant of the horizontal borehole placement method is being developed for soft sedimentary rock and uses tunnel and borehole liners to control rock creep.

For application in crystalline rock and hard sedimentary rock, the impact of the open gap between the borehole liner and the rock on the long-term repository safety would need to be addressed.

In the ONDRAF/NIRAS-type variant of the horizontal borehole placement method, the container is surrounded by a concrete buffer, which is intended to provide an alkaline environment to protect the steel container from corrosion. For application of this placement method in Canada, there is a need to assess the effectiveness of the concrete buffer to protect both the copper or steel containers from corrosion under expected environmental conditions in crystalline rock and sedimentary rock in Canada.

7.3 Horizontal Tunnel Placement Method

7.3.1 CTECH-type Variant of the Horizontal Tunnel Placement Method

The CTECH-type variant of the horizontal tunnel placement method, developed for a crystalline rock environment, includes a complex placement tunnel sealing system and requires a complex method for placing two containers simultaneously into the tunnel followed by the placement of additional buffer blocks below and above the containers. This placement method is not considered as a favourable alternative for application in any geological media because it would require significant effort to develop and demonstrate technologies for fabrication and placement of the sealing materials, and technologies for placing the containers in a manner that did not disturb the installed blocks of sealing material before the blocks of material are placed below the container. Any disturbance to this block array before block placement is complete could potentially affect the repository safety.

7.3.2 NAGRA-type Variant of the Horizontal Tunnel Placement Method

The NAGRA-type variant of the horizontal tunnel placement method is developed specifically for hard sedimentary rock by NAGRA. As suggested by NAGRA, this placement method is also considered to be applicable for soft sedimentary rock with the addition of a tunnel liner. In this method, the container will be placed on a highly compacted bentonite pedestal in the tunnel, and the remaining space in the tunnel will be backfilled with particulate bentonite buffer material.

Work to date indicates that the achievable dry density of the as-placed particulate bentonite buffer would be too low to suppress microbial activity and the potential microbially influenced corrosion of containers in relatively low salinity environments in crystalline rock. Development of a suitable bentonite buffer composition and placement method to achieve the necessary as-placed density to suppress microbial activity in a Canadian crystalline rock environment would be required.

The high groundwater salinity expected in hard and soft sedimentary rock in Canada would suppress the microbial activity in the lower density particulate bentonite and the potential of microbially influenced corrosion of containers.

The NAGRA-type horizontal placement method is considered to be a viable option for both hard and soft sedimentary rock. It could be considered for crystalline rock if it can be confirmed that particulate bentonite with adequate as-placed dry density to suppress microbial activity can be achieved.

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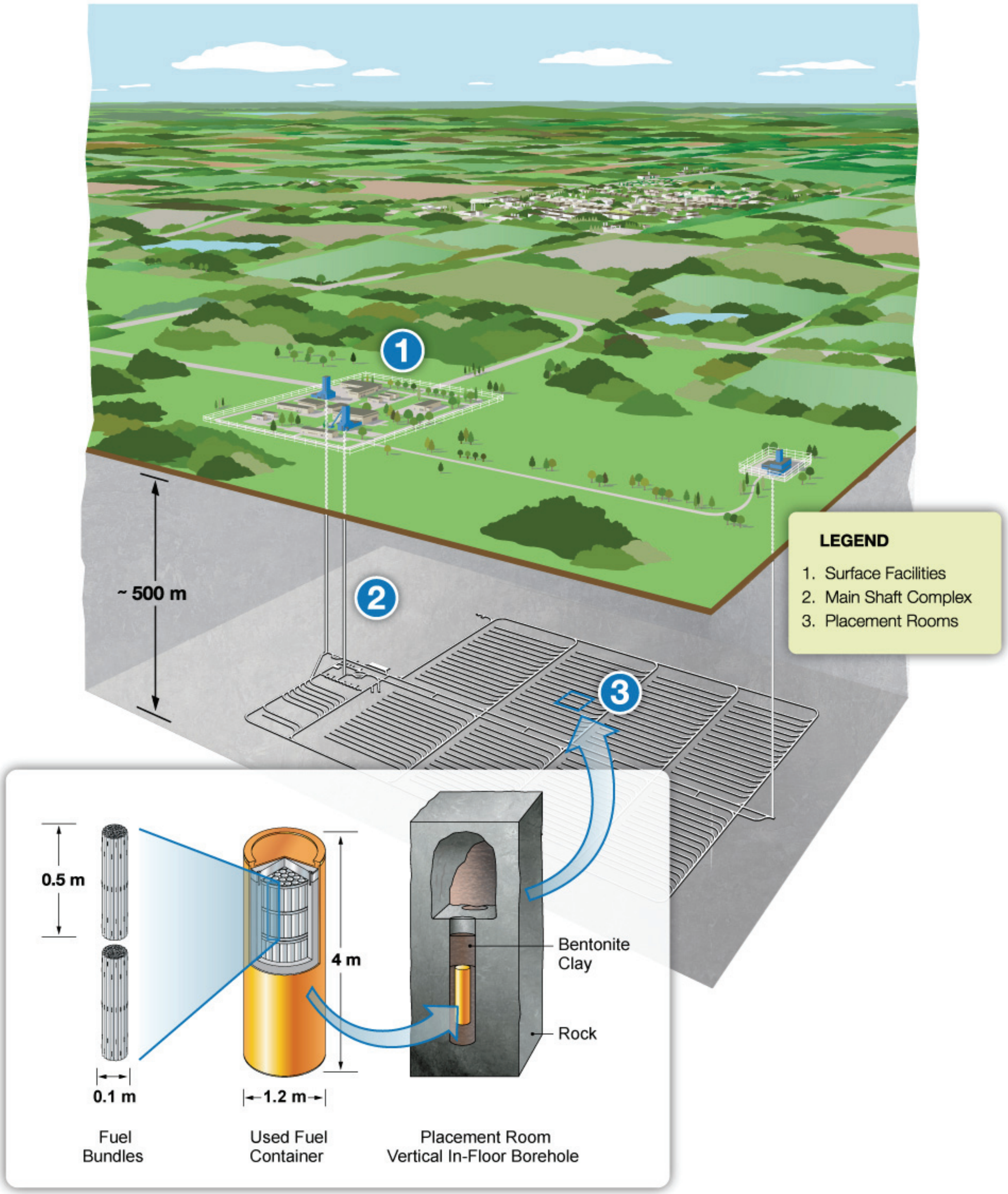

Figure 1: Illustration of APM Deep Geological Repository

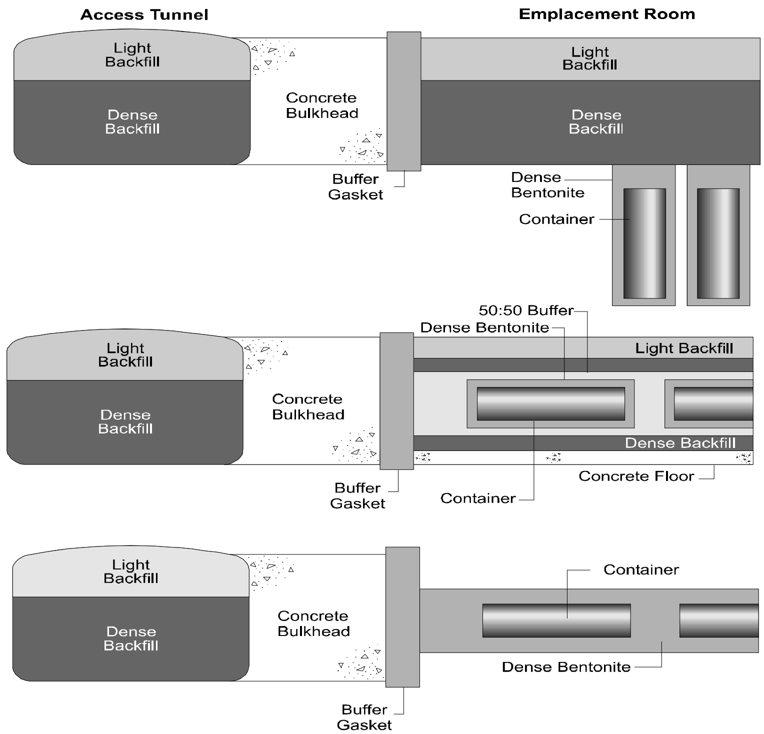

Figure 2: Schematic Representations of Three Container Placement Methods (In-floor Borehole, Horizontal Tunnel and Horizontal Borehole)

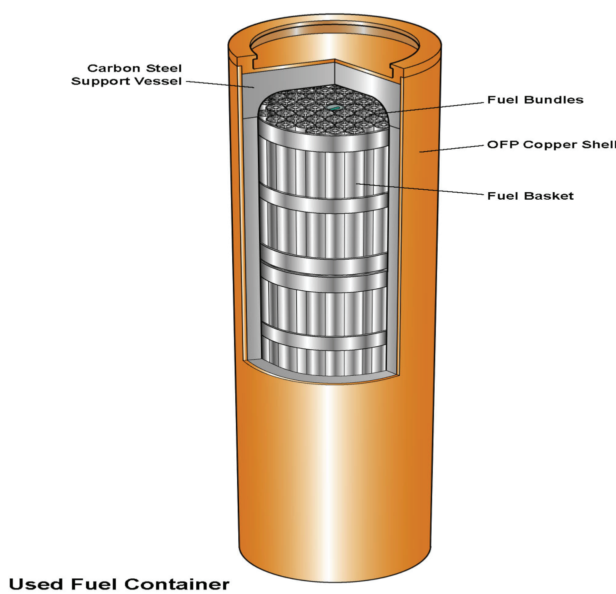

Figure 3: Typical Copper-shell Used-fuel Container for a Deep Geological Repository

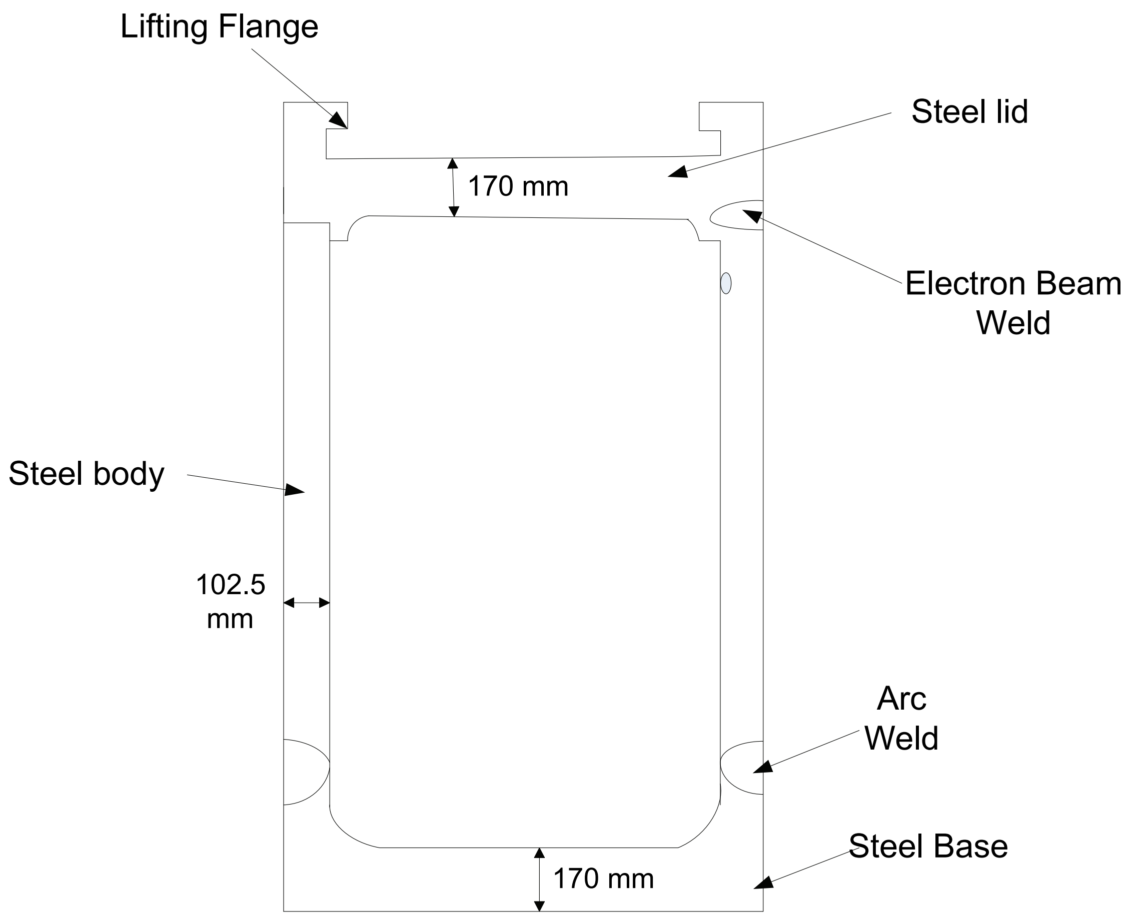

Figure 4: Typical Steel-shell Used-fuel Container for a Deep Geological Repository

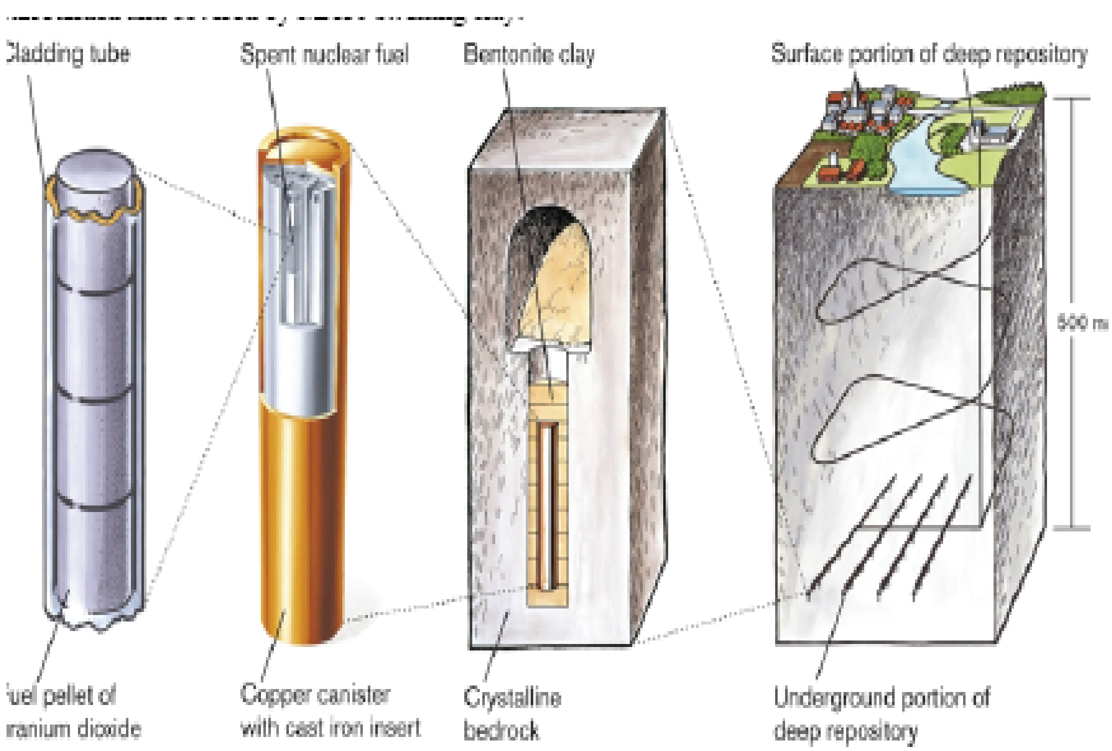

Figure 5: Swedish [and Finnish] In-floor Borehole Placement Method (KBS-3V) (SKB 1999)

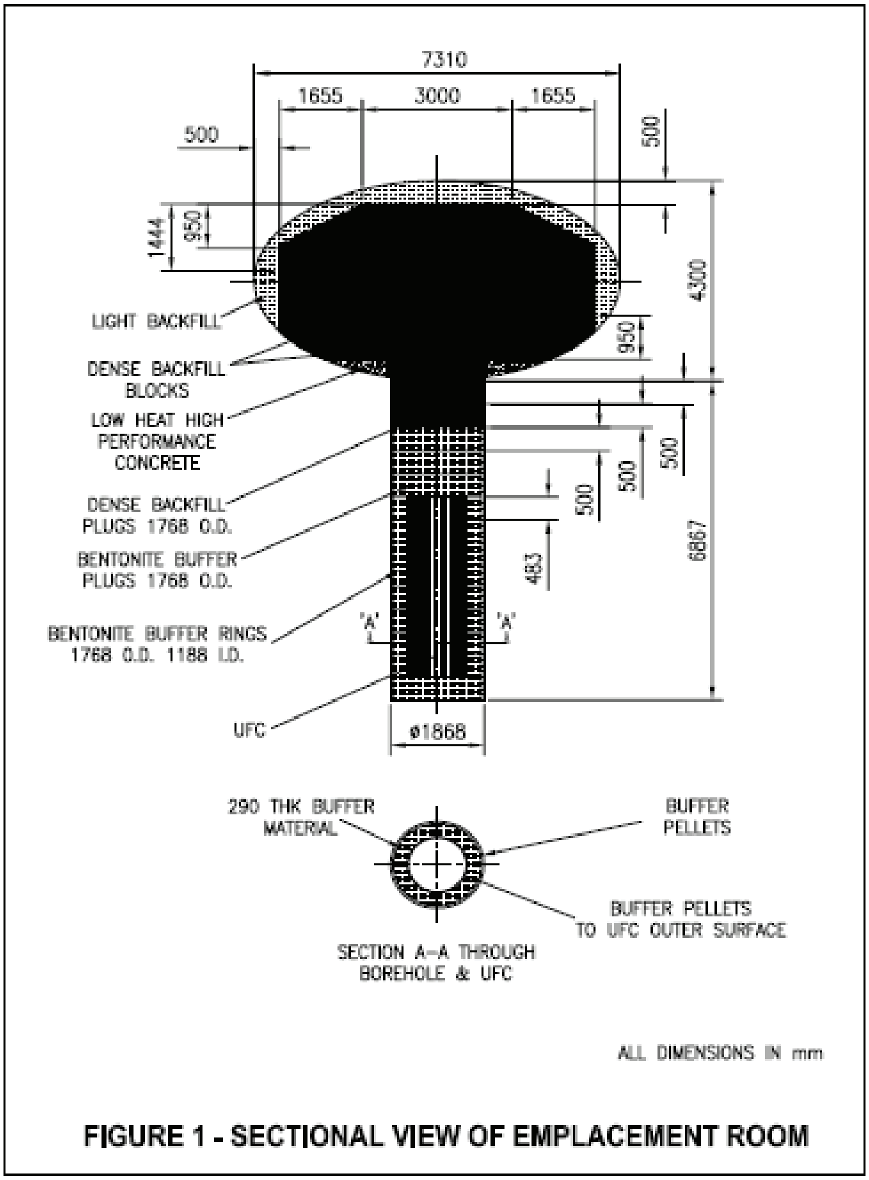

Figure 6: RWE NUKEM's In-floor Borehole Placement Method Design (RWE NUKEM 2003)

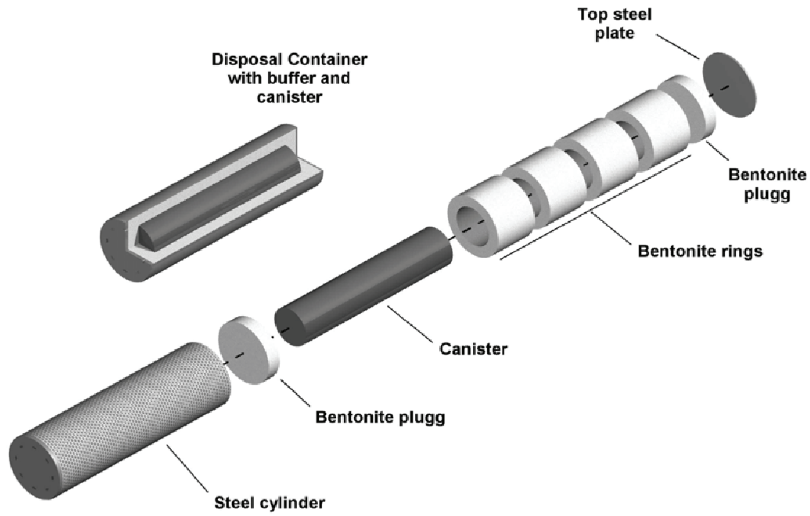

Figure 7: Super-container Package for the SKB's KBS-3H Design Concept (Lindgren et al. 2003)

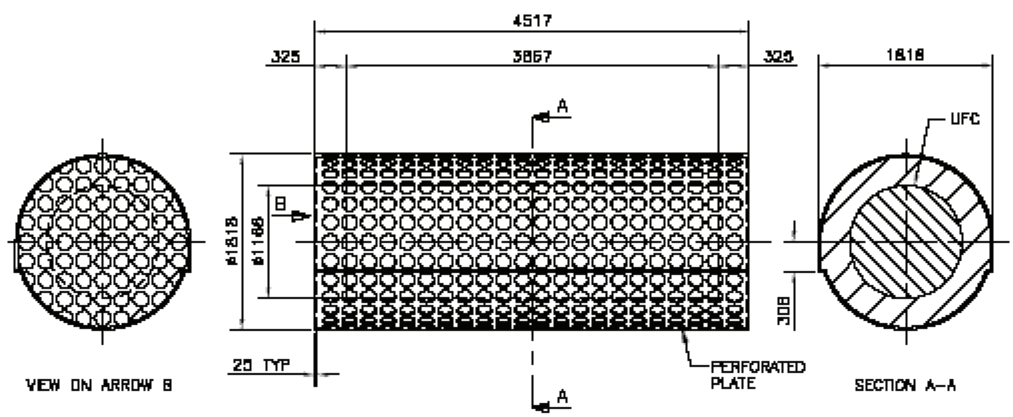

Figure 8: **Sectional Views of the Canadian-adaptation of a Supercontainer KBS-3H-type Horizontal Borehole Placement Method (RWE NUKEM 2004a)**

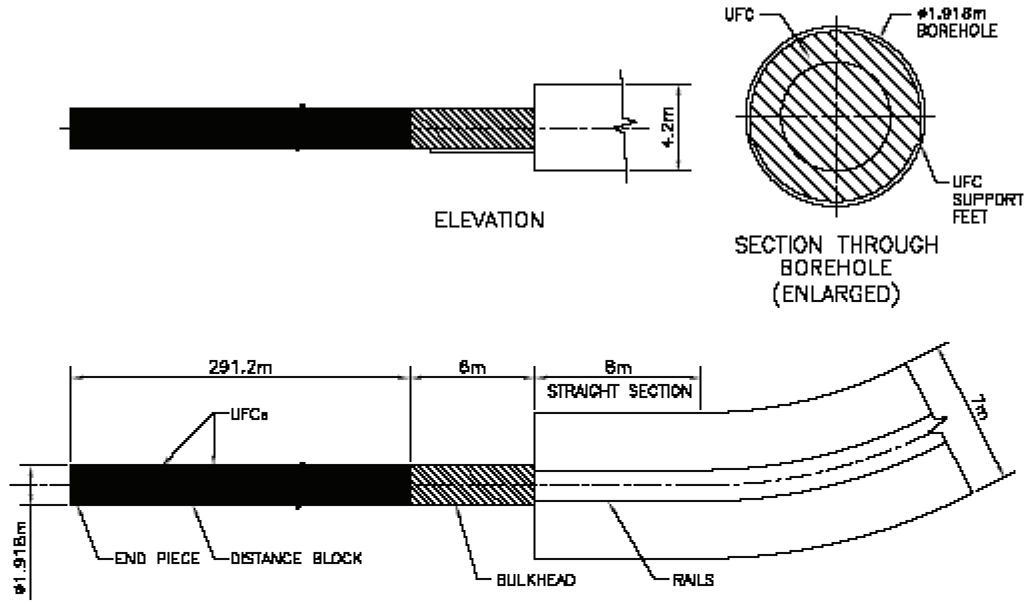

Figure 9: Longitudinal and Sectional View of the Canadian KBS-3H-type Horizontal Borehole Placement Method (NUKEM 2004a)

Figure 10: Cross Sections of the Spent Fuel Container showing the outer steel shell and inner cast iron insert (ANDRA 2005b).

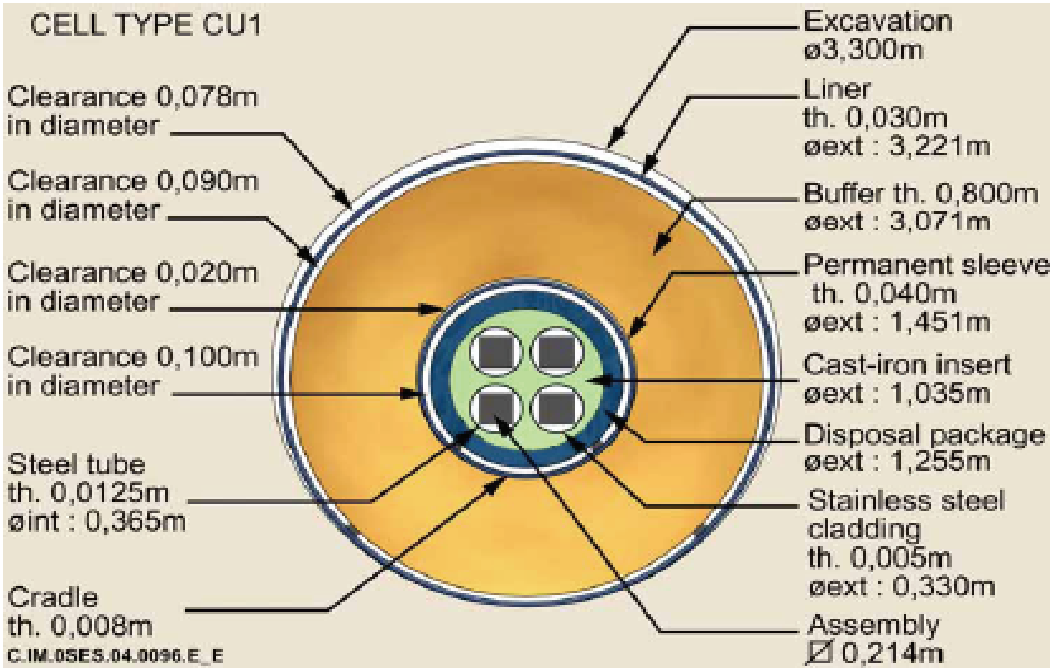

Figure 11: Cross Section through the ANDRA Spent Fuel Disposal Cell (ANDRA 2005b)

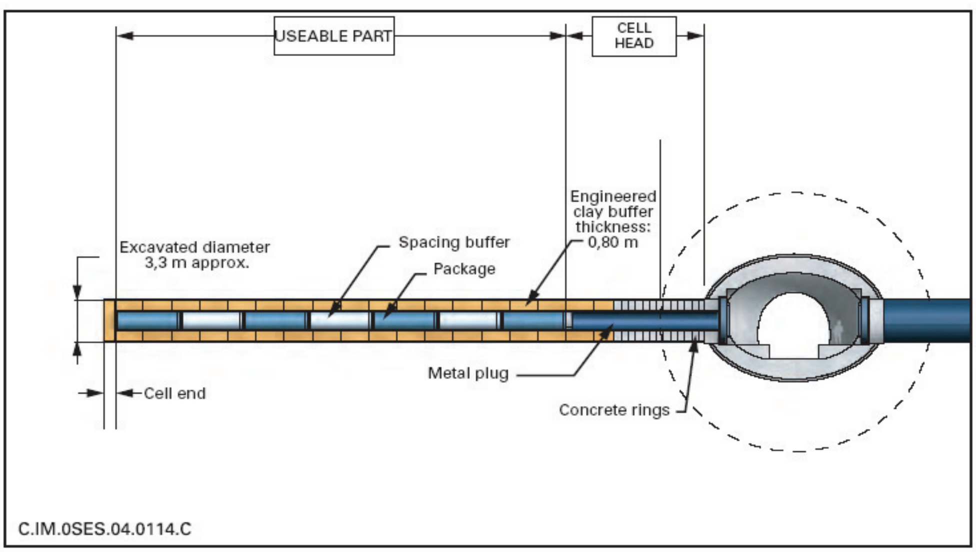

Figure 12: The ANDRA Disposal Cell for the Spent Fuel Containers (ANDRA 2005a).

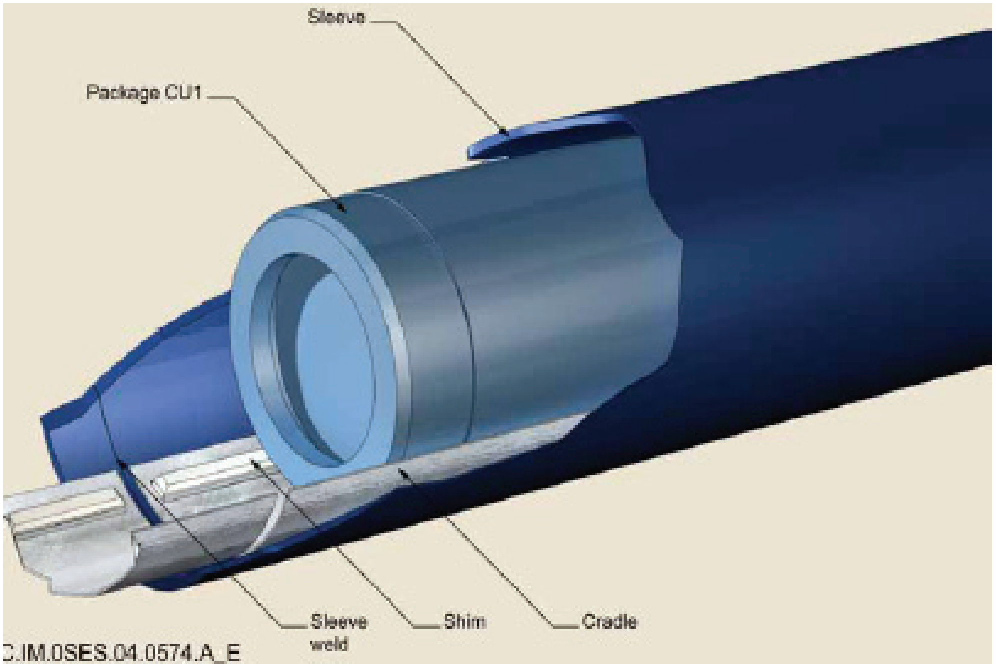

Figure 13: Internal Equipment of the Permanent Sleeve of the ANDRA Disposal Cell (ANDRA 2005b).

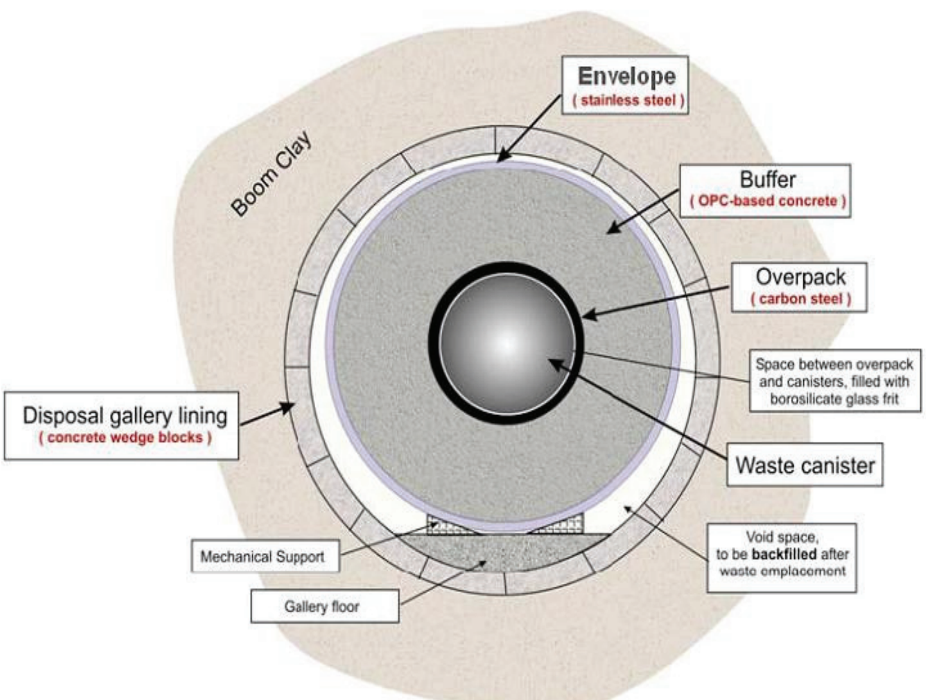

Figure 14: Schematic of the ONDRAF/NIRAS Horizontal Borehole Placement Method using the Supercontainer (Bel et al. 2006)

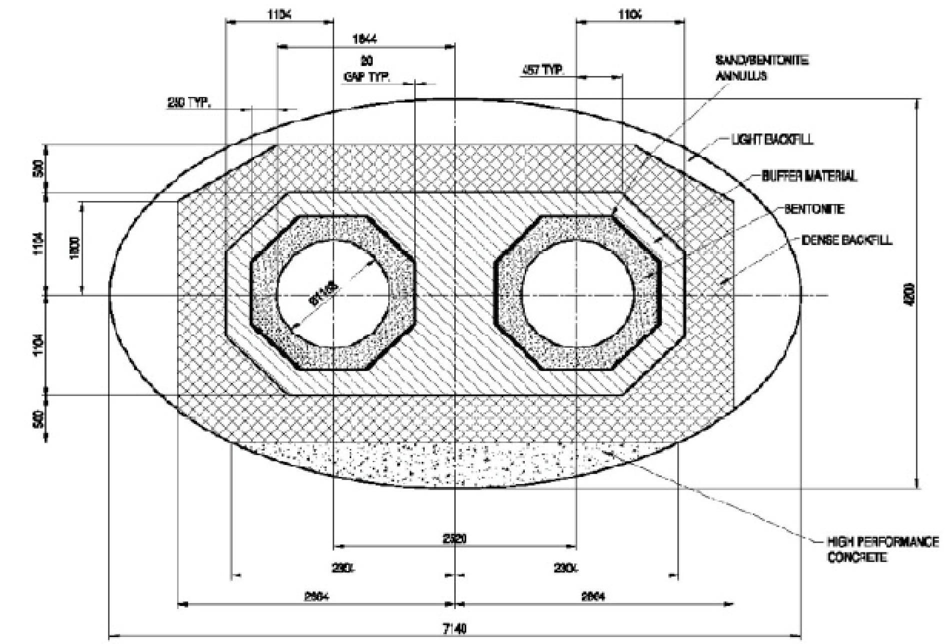

Figure 15: CTECH In-Room Placement Cross Section (CTECH 2002)

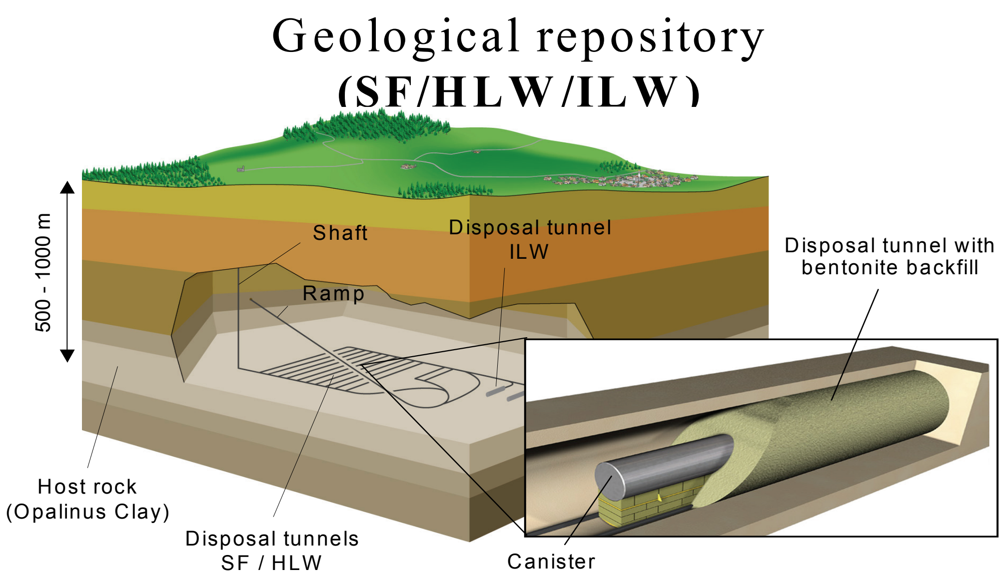

Figure 16: Conceptual Arrangement of a Swiss Deep Geological Repository in Opalinus Clay (NAGRA 2002)