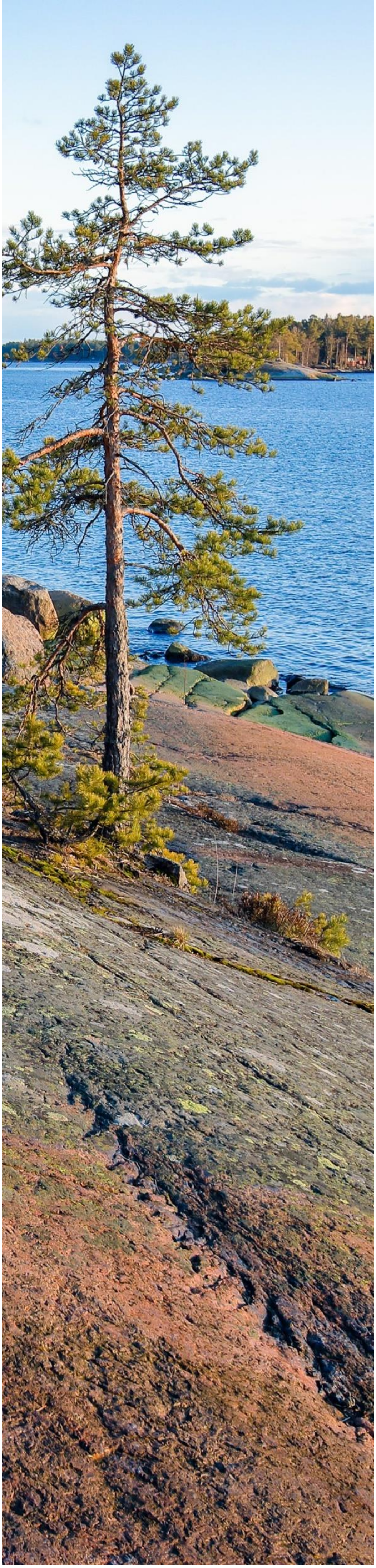

Technical report

Concept Description for Norwegian National Disposal Facility for Radioactive Waste

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ABSTRACT

The first concept description (in 2020) for a Norwegian National Facility for nuclear waste disposal is described in this report. The facility is described to act as a final repository for all radioactive waste generated so far, mainly the decommissioning waste from Norwegian research reactors in Halden and Kjeller, and the waste that will be generated in Norway over the 100 years following the commissioning of the facility.

The concept description for the National Facility contains the following repository types:

- Intermediate depth repository for very low, low and intermediate level waste,
- Deep geological repository (DGR) for high level waste,
- Deep borehole repository for high level waste as an alternative to the DGR,
- Landfill-type repository as an option for non-radioactive decommissioning waste, mainly soil and concrete.

The disposal facility concept description acts e.g. as a basis for further design of facilities and production of alternative combinations for selecting the types of facilities for further studies. The final concept might not include all the repository types listed above.

The underground repositories have been designed for operations taking place at two levels: a repository for very low, low and intermediate level waste at intermediate depth (100 metres) and a DGR for high level waste at the depth of 400 metres. The DGR could be replaced by a deep borehole with a maximum depth of approximately 3500 metres. The deep geological repository design is based on the KBS-3V repository concept developed in Sweden and Finland. The feasibility of borehole disposal is discussed because the technology is less mature than KBS-3.

Packaging assumptions were done based on inventory data. Most of the waste is assumed to be packed outside the National Facility. The basic scenario for pre-disposal treatment of high level waste is oxidation of metallic uranium to uranium oxide. The alternative scenarios that have also been considered for spent fuel are no treatment at all and reprocessing resulting in vitrified high level waste or metallic intermediate level waste.

Activities related to planning, construction, operation, decommissioning and closure phases, with regard to operational safety and radiation safety, safeguards of nuclear materials, required systems and operation as well as overall schedule, are briefly described. Site selection and related activities and a preliminary design for the required buildings and facilities above ground are also described.

The concept description maintains maximum flexibility to allow changes in the design solutions. Waste acceptance criteria or other details are not locked down at this stage. The concept description will also be used for preliminary costing and scheduling analysis in the next phase of the project.

The feasibility of using the KBS-3 spent fuel disposal concept in disposing of Norwegian spent fuel is investigated in this report. Norway has operated several research reactors, and some of the fuel used in these reactors contains metallic uranium. Metallic uranium is unstable chemically compared to uranium oxide in commercial spent nuclear fuel, which typically is disposed of with the KBS-3 concept in Sweden and Finland. In this report, its disposal without any additional treatment is studied. The properties of metallic uranium and the related features, events and processes in the disposal facility are reviewed.

The number of KBS-3 canisters required to dispose the Norwegian spent fuel is preliminarily estimated. Various encapsulation options are investigated and their engineering requirement estimated for future use. Knowledge gaps and future work required for the use of the KBS-3 disposal concept are evaluated. The conclusion of this study is that the disposal of metallic uranium is possible with the KBS-3 concept, although uncertainties remain especially in the design of the canister internals. Preliminarily, 25 to 37 KBS-3 disposal canisters with varying lengths and internal designs are probably required for disposal.

Keywords: spent nuclear fuel, radioactive waste, disposal, repository, intermediate depth, deep geological repository, deep borehole, landfill, Norwegian National Facility, KBS-3

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ABSTRACT

1 Introduction

Norwegian Nuclear Decommissioning NND has signed a contract with Finnish AINS Group together with subconsultants VTT Technical Research Centre of Finland and BGE Technology GmbH of Germany. The group assists NND with the concept development and technical design for their disposal solution for radioactive waste in Norway.

Norway's inventory of radioactive waste is characterized by high level waste from the research reactors in Halden and Kjeller, taken out of operation. In addition, there will be low and intermediate level waste from the planned decommissioning of the research reactors and other nuclear facilities. Norway has also other low level waste generated by e.g. medical sector.

According to NND's preliminary plans, the spent nuclear fuel accumulated in the research reactors in Halden and Kjeller will be disposed of in a national facility. This nuclear waste facility, called Norwegian National Facility, could consist of underground repository facilities and other underground openings as well as a landfill repository and auxiliary facilities above ground. This report describes the proposed conceptual disposal plan for the National Facility. The report reflects the situation in 2020.

The disposal facility concept description provides the following:

- tools for communicating current planning stage to stakeholders, e.g. the authorities and general public,
- initial data for the scheduling and cost estimates for setting out the financial provisions for waste management,
- initial data for the further preliminary design of facilities,
- input for planning research and development activities regarding the different areas of disposal technology,
- guidance for bedrock surveys carried out in potential sites,
- guidance for assessing the feasibility of disposal,
- a part of the overall description of the entire project.

The Norwegian National Facility is proposed to consist of the following separate disposal systems:
- Intermediate depth repository for very low-level, low-level and intermediate level radioactive waste (VLLW, LLW and ILW),
- HLW repository: either an excavated deep geological repository or a deep borehole repository,
- Landfill repository for non-radioactive waste from decommissioning of the nuclear facilities in Halden and Kjeller.

The deep geological repository design is based on the KBS-3 repository concept developed by Swedish Nuclear Fuel and Waste Management Co (SKB) and Posiva Oy as well as alternative deep borehole solutions. The KBS-3 method in this report is restricted to placing the canisters into vertical holes drilled in tunnel floors.

The underground repositories have been designed for operations taking place at two levels: VLLW, LLW and LILW waste repository at the depth of 100 metres and deep geological repository for HLW either at the depth of 400 m or in deep borehole alternative at the depth of 3500 metres. For all underground repositories, the depth will depend strongly on the site geology and for the deep borehole alternative the detailed disposal concept, especially the chosen borehole and container diameter. The aim is to maintain maximum flexibility to allow changes in the design solutions. The repository at the depth of 100 metres will be in operation for 100 years. The HLW repository will be operated roughly for one year and closed roughly in three years. As technologies develop and more knowledge is accumulated, the disposal methods can be changed.

In this report the reference solution includes the following assumptions:

- The concept is assumed to rely on the existing public domain know-how and experience from Sweden, Finland and deep borehole concept transformed into a cost-efficient small-scale facility to be used for disposal of the finite volumes from the Norway legacy radioactive waste.
- Waste properties and inventories, container designs and other predisposal waste handling, conditioning or treatment are out of the scope of this report. Assumptions only are made of the previous issues to complete the concept description.
- In DGR, the canisters are to be deposited in a vertical position in the holes drilled in the tunnel floors on the level of -400 metres, i.e. the KBS-3V solution.
- Canisters and waste packages will be transported via an access tunnel down to the repository level or via a deep borehole in the deep borehole alternative.
- The HLW canisters and most of the other radioactive waste packages are transported from the encapsulation plant and other packaging facilities to the National Facility.
- The underground repository facilities are located on two levels, at an approximate depth of 100 and 400 metres (in deep borehole alternative at the depth of 3500 metres).
- The deposition tunnels are backfilled using bentonite.
- Blasted rock and crushing plant, explosives storage, district heating plant, backfill manufacturing plant and encapsulation plant are located outside the National Facility.
- Building code type regulations are followed instead of pure mining law as is done in Finland for example.
- Surface structures are situated on a flat site and described only for the operational phase.

According to the Nuclear Energy Act, the Norwegian government can issue general regulations that concern the safety, security arrangements and emergency response arrangements or rescue operations. Regulatory guides that detail the regulations of the Norwegian Government are provided by Radiation and Nuclear Safety Authority DSA. It is expected that regulatory requirements in Norway develop in the coming years and thus applicable international standards are also used in this work.
Chapter 2 of this report presents the long-term safety concepts and the initial material for planning and design work. It also includes the basic data of radioactive wastes to be disposed of. Chapter 3 presents a summary description of the entire facility complex and overall schedule and Chapter 4 describes the site selection process and activities needed at the potential site. Facilities above ground are described in Chapter 5.

The implementation, operation, decommissioning and closure of the different parts (intermediate depth, deep geological, deep borehole and landfill repositories) of the National Facility are presented in Chapters 6-9. For each repository type, this includes a presentation of facilities, systems, construction process, operational activities, backfilling and closure.

The preparation of this report has been led and coordinated by Antti Ikonen (AINS). This study has been authored by Antti Ikonen (Chapters 1, 3, 5, 6, 7 and Sections 2.1.1-2.1.2, 2.2.6-2.2.9 and 2.2.11), Ari Gardemeister (AINS 3D-modelling and figures), Timo Saanio (AINS, Overall schedule) and Suvi Karvonen (VTT, Chapter 9, Sections 2.1.4, 2.2.3-2.2.5 and 2.2.10). Joachim Engelhadt (BGE-TEC) and Tilman Fischer (BGE-TEC) have authored Chapter 8 and Section 2.1.3 and Toivo Wanne (BGE-TEC) Chapter 4. Shared Chapter 10 and Section 2.2.1 has been authored by Antti Ikonen and Suvi Karvonen. Shared Section 2.2.2 has been authored by Antti Ikonen, Suvi Karvonen and Toivo Wanne. Annika Hagros from AINS has reviewed this report.

2 Design Basis

2.1 Safety concepts

2.1.1 Intermediate depth repository concept

The disposal system is conceptually divided into components as shown in Figure 2-1. The division helps in defining the safety functions for each component and modelling their evolution in the performance assessment.

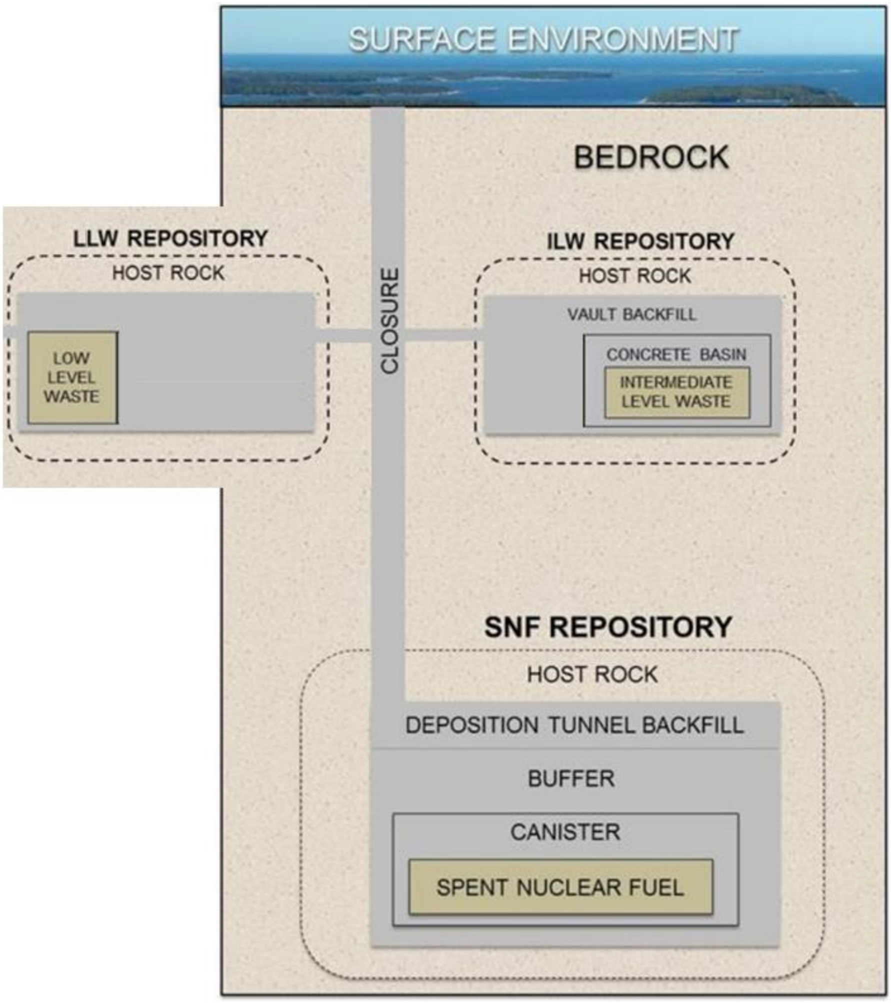

Figure 2-1. Conceptual representation of components of the disposal system. The waste hall on the left illustrates LLW (and VLLW) disposed in the hall and the one on the top right ILW and packages surrounded by concrete barriers inside a backfilled waste cavern. The deposition tunnel down illustrates HLW and canisters surrounded by buffer and deposition tunnel backfill barriers (modified from Posiva 2017 and Nummi 2018). Deep borehole repository for HLW is an alternative to the deep SNF repository (DGR).

The components are defined as in Nummi (2018):

- Low level (and very low level) waste packages: waste disposed in the repository without additional engineered barriers. Waste mainly consist of contaminated materials, and the waste containers are assumed to be steel drums. Some wastes can also be disposed without a container.
- Intermediate level waste packages: intermediate level waste and its containers, which are disposed of in the repository hall. Intermediate level waste includes mainly activated materials and

some solidified liquid waste. Waste containers are concrete containers for the decommissioning waste.
- Concrete barriers: concrete structures around the intermediate level waste packages. Barriers include a concrete basin with its backfilling in the ILW hall.
- Waste halls: halls excavated in the bedrock hosting the waste (Figure 2-2).
- Closure: Structures designed to separate the repository from the surface environment and provide mechanical support for the concrete barriers. Closure includes concrete plugs and backfilling in the waste halls and tunnels.
- Bedrock: Bedrock at the disposal site hosting the repository serving as a natural barrier.
- Surface environment: Surface environment that may receive radionuclide releases from the repository system.

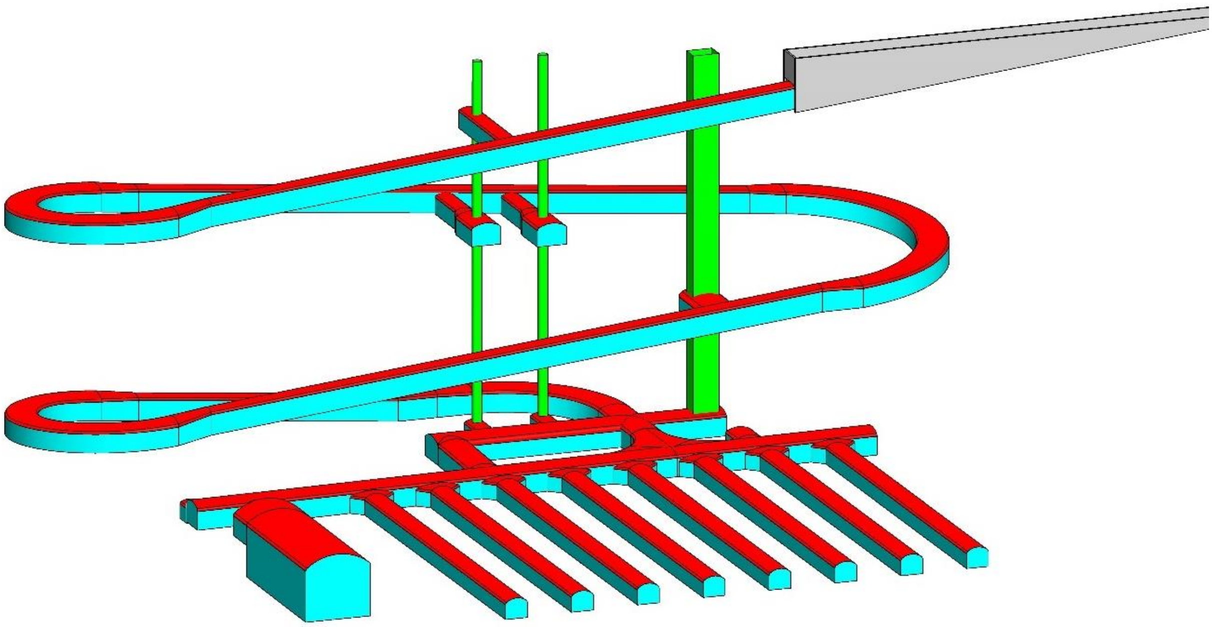

Figure 2-2. Intermediate depth repository for VLLW, LLW and ILW waste. Figure AINS.

Safety features

The safety features assigned to each component are listed in Table 2-1, which also indicates how each safety feature is associated with the safety concept. Together the safety features form the basis for the long-term safety of the disposal. The multibarrier system ensures that the radionuclide releases from the waste into the surface environment are effectively retarded and limited, even if a single or even several safety features do not fulfil their intended purpose. Likewise, the engineered barriers and the waste itself is protected from natural impacts or human actions by the bedrock and other engineered barriers (Nummi 2018).

Table 2-1. An example of safety features assigned to different components of the disposal system and to which part of the safety concept the specific safety feature contributes to (modified from Nummi 2018). Waste cavern is a synonym for waste hall.

Component	Safety features	Limited release from the waste	Slow transport	Isolation from the surface environment
Low level waste packages	The activity content in the low level waste is small compared to the overall activity in the repository.	✓		
Intermediate level waste packages	Slow corrosion of activated metals limits radionuclide releases.	✓		
	Solidification product limits and retards radionuclide release by slow leaching, low dissolution and sorption.	✓		
	Concrete containers limit and retard radionuclide transport by slow diffusion and sorption.		✓	
	Reactor pressure vessels and steam generators confine the reactor internals.		✓	
Concrete barriers	Concrete barriers protect the intermediate level waste packages by providing alkaline conditions and reducing mechanical impacts.	✓		
	Concrete barriers limit and retard radionuclide transport by sorption, slow diffusion and limited groundwater flow.		✓	
Waste caverns	Radionuclide releases are retarded by the dilution in the waste caverns.		✓	
	Waste caverns are located away from the major fracture zones and the amount of groundwater flowing through them is low.		✓	
Closure	Backfill protects concrete barriers against mechanical stresses.		✓	
	Closure limits the groundwater flow through the waste caverns.		✓	
	Backfill retards radionuclide transport by sorption.		✓	
	Closure reduces the likelihood of inadvertent human intrusion.			✓
Bedrock	Bedrock limits the groundwater flow in order to limit the radionuclide transport and protect concrete barriers.		✓	
	Bedrock allows sufficient gas transport, which prevents accelerated groundwater flow.		✓	
	Bedrock remains stable during the temperate period.		✓	✓
	Bedrock type and groundwater composition are favourable for radionuclide sorption.		✓	
	Repository currently resides in brackish groundwater which reduces the likelihood of drilled wells reaching the repository depth.			✓
	Bedrock reduces the impacts of natural phenomena and future human actions as well as the likelihood of inadvertent human intrusion.			✓
	Bedrock does not contain significant or exceptional deposits of exploitable natural resources attracting future human activities.			✓
Surface environment	Surface environment is similar to other coastal areas and does not attract any future human actions that could considerably impact the repository.			✓

Safety functions

Safety functions are formulated to demonstrate which design features are introduced to guarantee the safety of the disposal and to guide the formulation of scenarios. The safety functions are furthermore either those that

- confine, limit or retard the release and transport of radionuclides or
- protect other barriers and support them in meeting their safety functions.

In addition, it is implicitly assumed that a barrier is designed to be compatible with other barriers, i.e. a barrier does not have detrimental effects on other barriers by design, even though it is not explicitly listed as a safety function for any of the barriers. The safety functions assigned to different components are conceptually visualised in Figure 2-3 (Nummi 2018).

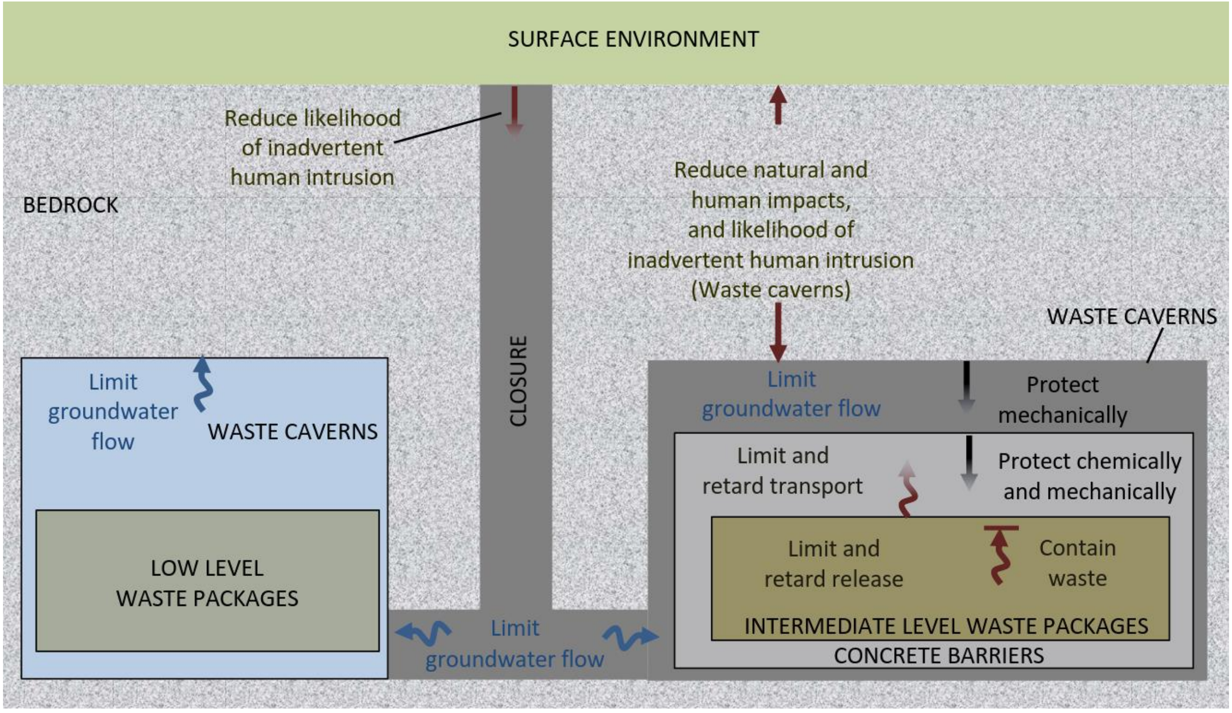

Figure 2-3. Conceptual representation of the safety functions assigned to different components. The location of the arrows indicates the component to which the safety function is assigned, unless otherwise indicated in parenthesis. For LLW (and VLLW) packages and bedrock no safety functions have been assigned (Nummi 2018).

2.1.2 Deep geological repository concept

Figure 2-1 shows a schematic example of the KBS-3 safety concept in the context of the whole facility and how safe disposal of spent fuel is achieved, taking into account the properties of the fuel, as well as the characteristics of the selected site.

Due to its long-term hazard, the spent fuel has to be isolated from the surface environment over a prolonged period of time. Safe disposal is therefore achieved by long-term isolation and containment. The features that favour long-term isolation and containment are shown as orange pillars and blocks in Figure 2-4. The figure also shows secondary features as green pillars and blocks which ensure that safety is maintained even in the event of releases of radionuclides over time. Another key element of the safety concept is the existence of multiple barriers so that it is unlikely that any single detrimental phenomenon or uncertainty could undermine the safety of the whole system. These primary and secondary features of the safety concept are described below (Posiva 2012a, Saanio et al. 2013).

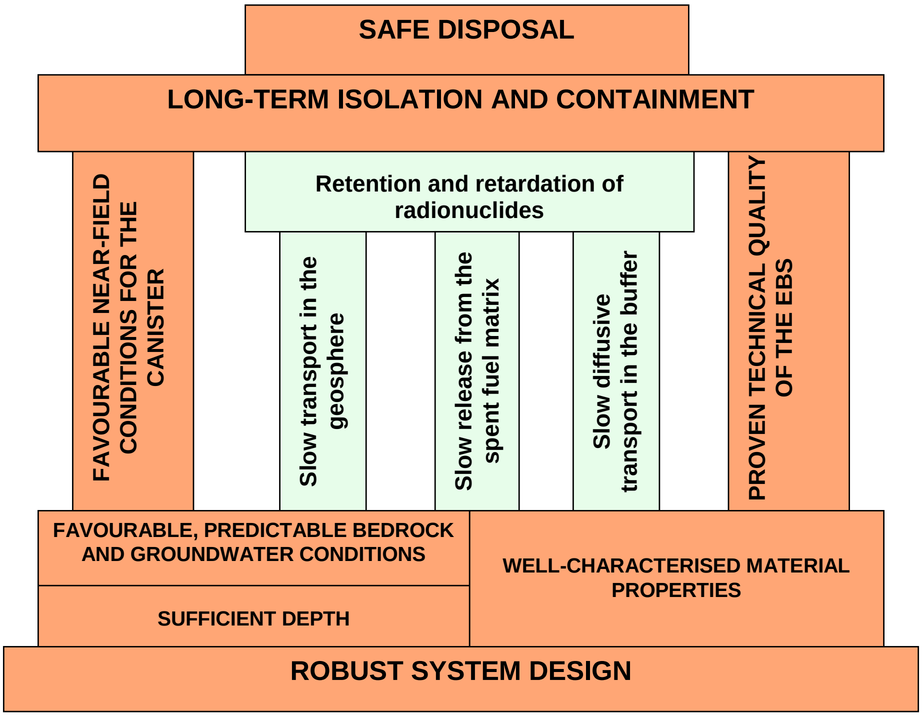

Figure 2-4. Main features of the safety concept for KBS-3 type disposal of spent nuclear fuel in crystalline bedrock. The safety concept is based on a robust design. The orange columns and bars illustrate the primary safety features and characteristics of the disposal system. The green columns and bars illustrate the secondary safety features that are particularly significant in the event that radionuclides are released from a canister (Posiva 2012a). In the so-called base case of the National Facility, the metallic uranium is treated with oxidation method to uranium oxide and aluminium cladding is replaced with stainless-steel cladding. The waste form is then assumed to have chemical properties equivalent to uranium oxide.

In the KBS-3 method, isolation of the radionuclides associated with the spent fuel is provided first and foremost by encapsulating the fuel in sealed gas- and water-tight copper-iron canisters. The likelihood of any radionuclide releases occurring from the canisters is kept small by an environment around the canisters that favours their longevity (favourable near-field conditions for the canisters) and by the proven technical quality of the engineered barrier system (EBS). The EBS includes: the canisters; a surrounding clay buffer that protects the canisters mechanically, hydraulically and chemically; a backfill of the deposition tunnels which supports the buffer and the rock; as well as closure structures, such as the backfill in the rest of the openings and the plugs and seals of transfer tunnels, shafts, access tunnel and research boreholes. These structures are designed to be compatible with the canister, the buffer, the backfill of the deposition tunnels and the host rock and support their performance. For example, backfilling and sealing of the repository cavities (including tunnels, shafts and boreholes) support the safety functions of the host rock by giving mechanical support to the rock and preventing the formation of transport pathways (flow paths). They also contribute to discouraging inadvertent human intrusion into the repository. The surface environment is not included since it does not have any safety function.

The system design should also be robust. This is achieved through a sufficient depth for the repository, favourable and predictable bedrock and groundwater conditions and well characterised material properties of both the bedrock and the EBS. The characterisation of the site and the strategy for repository design are focused on a volume of bedrock situated close to the repository at the depth of 400 metres below the ground surface. At such depths, favourable and predictable bedrock and groundwater conditions, such as reducing conditions, low frequency of water conducting fractures and slow movement of groundwater, can be found and the likelihood of inadvertent human intrusion is low.

Should any canister present an initial penetrating defect or be breached at a later time, the consequences of radionuclide releases for humans and other biota inhabiting the surface environment will be mitigated by the slow diffusive transport in the buffer and backfill, and slow radionuclide transport in the geosphere. Together, the engineered barriers and the rock provide retention and retardation of radionuclides.

Radioactive decay also continues during radionuclide transport. These features are illustrated in Figure 2-4 as secondary safety factors of the concept (as green columns and bars) because they only become relevant if the primary barrier, the canister, has failed.

The safety concept is based on a robust system design that also includes the design of the deep geological repository. In this context, the robustness of the system means that isolated faults in the design and implementation, or lack of information and uncertainties related to future conditions may not lead to a significant deterioration of the safety features. The design work needs to be developed iteratively between the repository designers and long-term safety assessors (Saanio et al. 2013).

Release barriers and their safety functions

- The safety functions of the barriers in Posiva's disposal system are presented in canister
- buffer
- deposition tunnel backfill
- closure structures and
- host rock.

Table 2-2, and a schematic illustration of the KBS-3V design is in Figure 2-5. In the KBS-3V design, the radionuclide release barriers are:

- canister
- buffer
- deposition tunnel backfill
- closure structures and
- host rock.

Table 2-2. Safety functions assigned to the barriers (EBS components and host rock) in Posiva's TURVA-2012 safety case for a KBS-3V repository (Posiva 2012a).

Release Barrier	Safety functions
Canister	• Ensure a prolonged period of containment of the spent nuclear fuel. This safety function rests first and foremost on the mechanical strength of the canister's cast iron insert and the corrosion resistance of the copper surrounding it.
Buffer	• Contribute to mechanical, geochemical and hydrogeological conditions that are predictable and favourable to the canister. • Protect canisters from external processes that could compromise the safety function of complete containment of the spent nuclear fuel and associated radionuclides • Limit and retard radionuclide releases in the event of canister failure.
Deposition tunnel backfill	• Contribute to favourable and predictable mechanical, geochemical and hydrogeological conditions for the buffer and canisters. • Limit and retard radionuclide releases in the possible event of canister failure. • Contribute to the mechanical stability of the rock adjacent to the deposition tunnels.
Host rock	• Isolate the spent nuclear fuel repository from the surface environment and normal habitats for humans, plants and animals and limit the possibility of human intrusion, and isolate the repository from changing conditions at the ground surface. • Provide favourable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers. • Limit the transport and retard the migration of harmful substances that could be released from the repository.
Closure	• Prevent the underground openings from compromising the long-term isolation of the repository from the surface environment and normal habitats for humans, plants and animals. • Contribute to favourable and predictable geochemical and hydrogeological conditions for the other engineered barriers by preventing the formation of significant water conductive flow paths through the openings. • Limit and retard inflow to and release of harmful substances from the repository.

In the case of SKB safety case, the spent fuel (or chemical form of UO_2) is also additionally considered a release barrier itself due to slow dissolution in repository conditions.

Closure refers to backfilling and sealing structures used elsewhere than in the deposition tunnels, such as in the access tunnel, the transfer tunnel and in shafts. These structures are necessary in construction because of technical reasons or due to operational safety, but, in some cases, they also have long-term safety functions. Their long-term safety functions are defined, for example, to avoid that the repository underground facilities (such as the access tunnel and shafts) compromise the safety functions of the host rock (e.g. in case they are not properly backfilled and sealed).

The function of the deposition tunnel plug is primarily to keep the backfill in place, and thus to contribute to the performance of the backfill. Other auxiliary components include grouting materials, and rock support structures. These components are not assigned safety functions. In most cases, however, they serve to protect the components that do have safety functions during the operational period and through the early evolution of the repository. For example, grouting protects the buffer and backfill from high, transient water flows prior to repository saturation, and prevents drawdown of surficial waters or upconing of deep (saline) groundwater, thus supporting the safety functions of the host rock. The overriding requirement regarding the design and construction of all engineered components is that their presence should not significantly impair the safety functions of other components (engineered or natural) (Saanio et al. 2013).

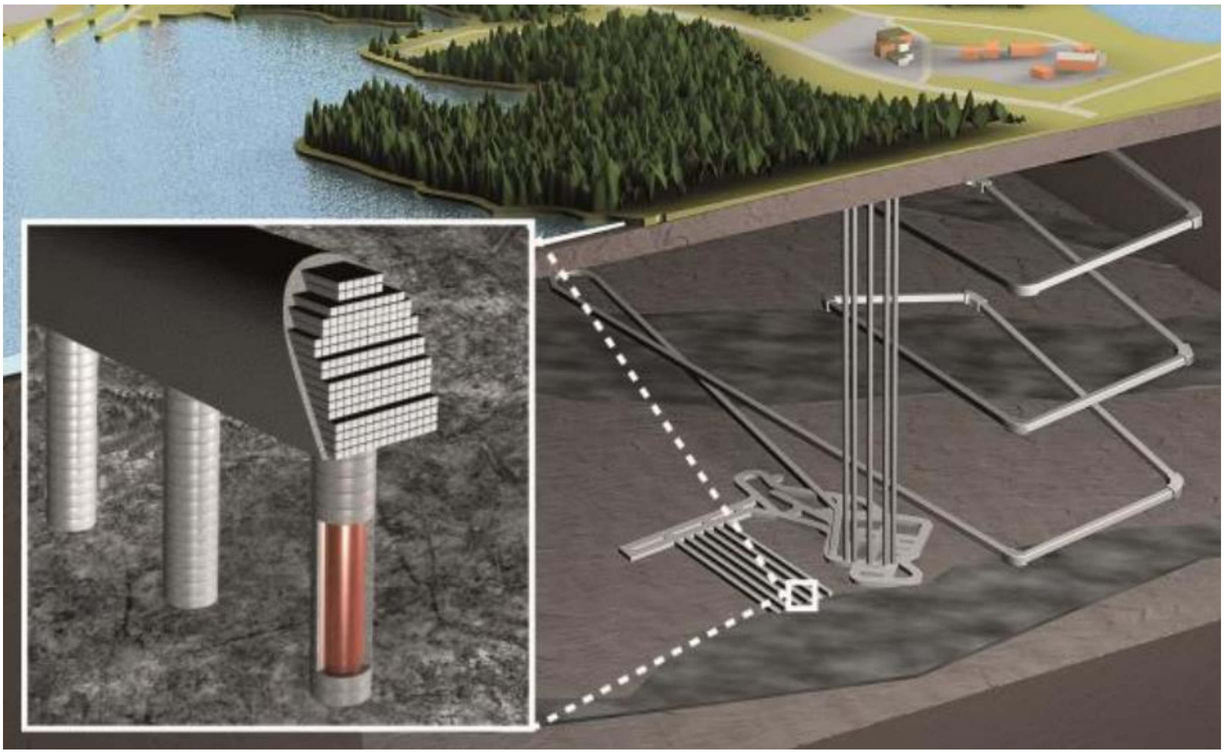

Figure 2-5. A schematic illustration of the KBS-3V repository design (Posiva 2017).

2.1.3 Deep borehole repository concept

Borehole disposal concept consists of drilling a borehole to a depth of several kilometres, emplacing nuclear waste canisters in the lower part of the borehole and then sealing the upper part of the borehole. The disposal concept is applicable in most host rock environments. Borehole disposal facilities consist of surface structures, such as disposal hall and emplacement rig, and the drilled deep borehole directly under the rig.

Due to the small amount of HLW in Norway, deep borehole disposal is a potentially attractive alternative to an excavated repository. A deep borehole is drilled into crystalline rock from the surface to the depth of about 3500 metres depending on the local geology and the disposal concept. Crystalline rocks are mechanically stable and hard, they have low permeability and often high thermal conductivity, which is of benefit for disposing heat-generating waste.

Waste canisters are placed in the lower section of the borehole. The upper section of the borehole above the emplacement section is sealed with a long-term barrier system. After successful disposal of the waste packages in the borehole, the facility closure phase begins. This is divided into decommissioning, backfilling and sealing of the borehole and site rehabilitation. The final phase is the institutional control period.

The safety case for such a concept places strong emphasis on the great depth of burial, which ensures that the waste remains isolated from the accessible environment. The safety concept of a borehole disposal system is very similar to that of deep excavated repositories (see Section 2.1.2). It relies on multi-barrier system that consists of canister, buffer, borehole backfill, borehole seal and the host rock. However, the safety concept has two significant differences compared with excavated repositories: the great depth of the disposal zone and the very compact geometry of the system.

2.1.4 Landfill repository concept

The waste deposited in the landfill repository will consist of decommissioning waste classified as non-radioactive. However, the repository is designed such that it could be capable of accepting very low level waste in case of future need, and the IAEA safety standards for near surface disposal apply also to this application considering a graded approach. In general, the long-term safety of a disposal facility for radioactive waste relies on passive engineering and natural features of the disposal system.

Containment and isolation are the main safety functions of the disposal system ensuring the passive post-closure safety. These main safety functions are provided by a system of engineered and natural barriers with multiple complementary and compatible lower-level safety functions preventing the release of harmful substances or retarding their migration into the biosphere to an acceptably low level set by applicable regulatory limits (IAEA 2014; IAEA 2011: requirement 8).

For example, the safety functions assigned to the different barriers can provide physical (e.g., through a low permeability) and chemical containment (e.g., by controlling pH and thus the solubility of certain radionuclides) (IAEA 2014). Isolation refers to the separation of the hazardous waste from the accessible biosphere by an appropriate repository design and the suitability of the chosen site. This includes also external events potentially detrimental for the safety performance of the disposal system, such as human intrusion (IAEA 2014). With respect to near surface disposal facilities, long-term safety is ensured by (IAEA 2014; 2011: requirement 4):

1. “The capability of the features of the disposal facility to contain the waste and isolate it from the biosphere;
2. The capability of the features of the site to contribute to the containment and isolation of the waste;
3. The limitations placed on the radiological inventory, mainly with regard to long lived radionuclides, that can be disposed in the facility;
4. The measures for surveillance and control of the disposal facility and its immediate surroundings that are applied to prevent or restrict any human activities that could disturb the facility barriers and lead to increased exposure.”

In addition, according to IAEA (2011 and 2014), the design of the low permeability barriers shall be done based on local external conditions (e.g. precipitation, changes in temperature, ground frost) and design requirements (e.g. target for the maximum allowed annual water infiltration into the repository). In order to limit the migration of radionuclides, this can be ensured by, for example, low permeability barriers with sorption capacity for the radionuclides and with cement present in the waste reducing the solubility of the radionuclides (IAEA 2011, 2014).

Since the site has not been selected yet, the following assumptions are made concerning the repository site:

1. The repository is built over a relatively flat site with ~2 metre thick overburden over solid bedrock.

2. The site is located on a tectonically stable area and no major faults or fracture zones are intersecting the selected site.
3. The groundwater level is assumed to be located ≥1.5 m below the ground surface, including annual fluctuations in the groundwater level. It is also assumed that the site is not located on any area that is considered important for groundwater resources and has limited connection to the surrounding areas through groundwater.
4. Based on a reference period from 1971-2000, the mean annual precipitation in Norway was 1600 mm with variation from 300 mm up to 3500 mm depending on the location (Hanssen-Bauer et al. 2017). Due to climate change, the mean annual precipitation is likely to increase (e.g. up to 18% in scenario RCP8.5) towards the end of the ongoing century (Hanssen-Bauer et al. 2017). Therefore, the design value selected for this study is set to 2000 mm of mean annual precipitation. In addition, heavy rainfalls and draughts are expected to be more common in the future, meaning increased risk for erosion of the cover structures of the repository.
5. The maximum depth of ground frost depends on the location (~1-3 m) in Norway being highest in the north and in mountainous areas (Statens Vegvesen 1976, 2005). For this study it is assumed that the maximum ground frost depth is 1.5 m, but this needs to be verified for the site chosen.
6. The risk of coastal flooding can be excluded and the site is not located in the vicinity of any lakes, rivers, creeks that could flood into the repository.

The concept description of the landfill repository consists of

1. **Foundation structures** of the landfill including natural and engineered barrier layers with the performance target to limit the dispersion of radionuclides and other possible contaminants into the groundwater and to the surrounding environment. In addition, the foundation layer provides stable foundation for the waste and helps preventing uneven settlements taking place in the repository and potentially deteriorating barrier structures.
2. **Waste form, waste packages (optional) and backfill material around the waste/waste packages.** The related performance target is to provide containment (physical and chemical) of the waste. In addition to ensuring chemical containment by its sorption capacity, in certain areas, backfill material might also have the function to serve as a drainage material.
3. **Cover structures** placed above or around the waste will have the performance targets to limit the ingress of water into the repository, protect the waste and barriers from ground frost, erosion and roots of the trees that have the ability to deteriorate performance of different barriers. The inclination of the cover layer shall be selected to enhance surface runoff but maintaining sufficient stability of the structure (avoiding creating slip planes).

In line with the IAEA safety standards (2011, 2014), these barriers have the safety functions to a) limit the ingress of water into the repository towards the waste and to b) limit the migration of leachate waters (with contaminants and possibly with some radionuclides) from the waste to the biosphere. Performance targets and design specifications for the barriers and structures in the landfill repository are discussed in detail in Section 9.1.1.

2.2 Basic parameters

The basic parameters for the design of the National Facility are compiled in this section.

2.2.1 Regulatory requirements

The National Facility is planned to answer all Norway's nuclear waste management needs and the development work is under way. The national legislation and safety requirements are under development at the same time, and there will have to be a well-functioning dialogue between the implementer and the regulator bodies.

In the following, some international regulations and standards are discussed as a basis for future Norwegian requirements for the National Facility. There are also some regulations from other countries documented to this Section that are recommended to be used in Norway.

IAEA Safety Standards

The International Atomic Energy Agency (IAEA) lists the specific aims for disposal of radioactive waste as (IAEA 2011):

- To contain the waste;
- To isolate the waste from the accessible biosphere and to reduce substantially the likelihood of, and all possible consequences of, inadvertent human intrusion into the waste;
- To inhibit, reduce and delay the migration of radionuclides at any time from the waste to the accessible biosphere;
- To ensure that the amounts of radionuclides reaching the accessible biosphere due to any migration from the disposal facility are such that possible radiological consequences are acceptably low at all times.

This set of guidelines can be used as a starting point for a sovereign country, such as Norway, to develop its own national legislation and national nuclear waste management safety related requirements. These requirements will be different for each stage of the National Facility's operation: the planning and construction phase, the operational phase and the decommissioning, closure and post-closure phases.

Other organizations

In addition to the IAEA, several other international organizations have developed their own safety standards and guidelines that can be used as a basis for the National Facility design. These organizations include e.g. OECD NEA (Nuclear Energy Agency) and WENRA (Western European Nuclear Regulators' Association). OECD NEA for example has a database of nuclear waste management country reports and updates while IAEA's Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management includes country reports of their waste management practices (see e.g. Finland's country report in STUK 2017). WENRA, on the other hand, has concise recommendations on

1. decommissioning (WENRA 2015)
2. storage (WENRA 2014b)
3. treatment and conditioning (WENRA 2018)
4. disposal facilities (WENRA 2014a)

In addition to these expert organisations, European Union has established a nuclear waste management directive (EU 2011) that has been largely built on nuclear waste management experiences of the member states. While Norway is not an EU member state, it can still benefit from following the EU nuclear waste management directive that sets a more or less comprehensive set of requirements for responsible and safe management of spent fuel and radioactive waste (EU 2011):

1. National framework (overall policy, legislative, regulatory and organisational framework allocating responsibility and providing coordination between relevant bodies
2. Competent regulatory authority
3. Licence holders (main responsibility for nuclear waste management lies with licence holders)
4. Expertise and skills (education, training, R&D, competence management)
5. Financial resources
6. Transparency (information of nuclear waste management must be made available for workers and general public)
7. National programme (nuclear waste management from generation to disposal)
8. Contents of national programme (how the national programme is planned to be implemented)

As Norway is not a member of EU, it can use the directive as a potentially useful reference in the preparation work for the National Facility.

The above-mentioned references can be directly used for the National Facility profiting from lessons learned without having to follow the costly and time-consuming trial and error path of the pioneers. This will speed up the development of national licensing requirements as these are usually based on national legislation, international recommendations and good scientific research.

Safety requirements as design basis for National Facility

The safety requirements for National Facility can be divided into two categories: operational safety, including radiation safety and fire safety, and long-term safety.

For radiation safety during operational phase, the disposal facility is considered to be a source of radiation that is under regulatory control in a planned exposure situation. Radioactive release can be verified, exposures can be controlled, and actions can be taken where necessary. During operation, radiation doses should be kept as low as reasonably achievable and within an applicable system of dose limitation. No releases of radionuclides, or only very minor ones are expected during the normal operation of a radioactive waste disposal facility. Even in the event of an accident involving the breach of a waste package on the site of a disposal facility, releases are unlikely to have any radiological consequences outside the facility. Radiation safety during operation can be achieved through the well-known engineering solutions. (IAEA 2011).

Long-term radiation safety is a considerably more complex issue than operational safety. It is demonstrated through a safety case, i.e. the collection of arguments and evidence to demonstrate the safety of a disposal facility. IAEA indicative requirements for long-term safety are the following (IAEA 2011):

1. The dose limit for members of the public for doses from all planned exposure situations is an effective dose of 1 mSv in a year. This and its risk equivalent are considered criteria that are not to be exceeded in the future.
2. To comply with this dose limit, a disposal facility (considered as a single source) is so designed that the calculated dose or risk to the representative person who might be exposed in the future as a result of possible natural processes affecting the disposal facility does not exceed a dose constraint of 0.3 mSv in a year or a risk constraint of the order of 10–5 per year.
3. In relation to the effects of inadvertent human intrusion after closure, if such intrusion is expected to lead to an annual dose of less than 1 mSv to those living around the site, then efforts to reduce the probability of intrusion or to limit its consequences are not warranted.
4. Natural processes include the range of conditions anticipated over the lifetime of the facility and events that could occur with a lesser likelihood. However, extremely low probability events would be outside the scope of consideration. Risk due to the disposal facility in this context is to be understood as the probability of fatal cancer or serious hereditary effects.
5. If human intrusion were expected to lead to a possible annual dose of more than 20 mSv to those living around the site, then alternative options for waste disposal are to be considered, for example, disposal of the waste below the surface, or separation of the radionuclide content giving rise to the higher dose.
6. If annual doses in the range 1–20 mSv are indicated, then reasonable efforts are warranted at the stage of development of the facility to reduce the probability of intrusion or to limit its consequences by means of optimization of the facility's design.
7. Similar considerations apply where the relevant thresholds for deterministic effects in organs may be exceeded.

The Norwegian national regulatory authority can set different requirements for the National Facility. Currently, the following requirements must be observed according to the Norwegian Act on Radiation Protection and Use of Radiation:

1. In operational phase maximum dose is for 20 mSv/y for employees and 1 mSv/y general public during normal operation
2. For long term safety, the Act sets the limit for releases to 0.25 mSv per year

For comparison, corresponding Finnish requirements provided in STUK YVL D.5 Guide (STUK 2018) are as follows:

1. For operational safety; the disposal facility and its operation shall be so designed that the annual dose to the representative person remains below the values indicated below (Sections 22b and 22d of the Nuclear Energy Decree 161/1988):
    1. 0.1 mSv as a result of an anticipated operational occurrence;
    2. 1 mSv in the event of a Class 1 postulated accident; and

3. 5 mSv in the event of a Class 2 postulated accident. [2018-02-13]

2. For long term safety; The disposal of nuclear waste shall be so designed that the radiation impacts arising as a consequence of expected evolution:

1. the annual dose to the representative person remains below the value of 0.1 mSv;
2. the average annual doses to other persons remain insignificantly low.

These constraints shall be applied over an assessment period, during which the radiation exposure of humans can be assessed with sufficient reliability, and which shall extend, at a minimum, over several millennia (Section 22d of the Nuclear Energy Decree 161/1988). [2018-02-13]

Long-term safety is provided through the repository design by passive means to fulfil the requirements and shall not rely on extended monitoring or maintenance of the site.

Safety classification

In order to ensure the safe operation and long-term safety of the disposal facility, for the design, construction and operation of the facility as well as for the sealing off of the repository:

- proven or otherwise carefully examined high quality technology shall be employed
- advanced quality assurance programmes shall be applied
- an advanced safety culture shall be maintained.

The systems, structures and components of a nuclear waste facility shall be classified on the basis of their significance in terms of the operational safety of the facility or the long-term safety of disposal. The required quality level of each classified object, and the inspections and testing necessary for verifying the quality, shall be adequate as regards the significance of the object in terms of safety.

Systems and structures or functions important to the safe operation of a disposal facility typically include:

- handling of the disposal canister
- fire protection in compartments containing radioactive materials
- ventilation and filtering at the controlled zone
- radiation monitoring.

Systems, structures and components or functions important to long-term safety and subject to safety classification typically include:

- disposal canister
- the disposal canisters inspection
- the buffer materials and sealing structures surrounding the spent fuel canisters and the layout, excavation and sealing of the underground disposal facility.

In order to ensure the long-term safety of disposal, the canister deposition hole with its buffer materials is included within the scope of safety classification. The integrity of rock walls in the hole, the amount of seepage, cleanliness of the hole as well as the tolerances for the position and shape of the hole are acceptance criteria for the deposition hole (Saanio et al. 2013).

Requirements related to the function of systems and reduplication of them

The functions of the disposal facility that could, upon failure, cause substantial release of radioactive substances or accidents leading to personnel exposure to radiation, must be verified. Segregation and diversity principles should be applied in such verification where possible. In the case of individual failure, the functions that will be verified are determined according to the Safety Class and are typically:

- braking of transferring vehicle
- radiation measurements in spaces where it is possible to be exposed to large doses of radiation
- activating a fire alarm or putting out fire in spaces where a fire could cause a substantial radiation danger or other danger
- power supplies that are used for operational safety of the facility.

The handling systems for spent fuel disposal canisters or other waste packages shall be designed so that a single equipment failure cannot cause a drop accident or another kind of accident where significant amounts of radioactive substances could be released from a package or canister. A radiation hazard shall not be caused as a consequence of the loss of the driving power of these systems.

The disposal facility shall be designed so that its operational safety is, as far as possible, based on passive systems (Saanio et al. 2013).

Anticipated operational transients and accidents

An anticipated operational transient refers to a safety-related incident, which is estimated to occur less frequently than once a year but has a significant probability of occurring at least once during the operational period of the facility. As a result of an operational transient, spent nuclear fuel or radioactive waste may be damaged and a canister broken so that dose rates and radioactive substance concentrations increase within the disposal facility, or that radioactive substances may be released into the environment of the facility.

A postulated accident is an event that is used as a design basis for the safety functions of the disposal facility and that has a low probability of occurring during the operational period of the facility. As a result of a postulated accident, spent nuclear fuel or radioactive waste may be severely damaged and a canister or package broken so that large amounts of radioactive substances are released into the premises or significant amounts of radioactive substances are released into the environment. Some of the postulated accidents are used as the design basis for the safety functions of the disposal facility.

In Finland, the operational safety analysis of the HLW disposal facility has not revealed a possibility for a significant accident threatening nuclear safety provided that the systems are designed and used in compliance with the requirements. However, the risk of a major release is created if the fire safety design of the vehicle used for transferring and installing the canister is not compliant with requirements (the fire load shall be small enough so that it cannot damage the canister inside the radiation shield in any hypothetical case of fire). In order to ensure that fire protection in the facility remains as a sufficiently important aspect of design work, a fire in the installation vehicle - that shall not result in a loss of canister tightness - was chosen as the dimensioning design basis for nuclear safety in the HLW repository.

The radiation doses resulting from the undisturbed operation of the facility, from anticipated operational incidents and from postulated accidents shall be estimated. The dose shall be estimated for the person being most exposed in the vicinity of the disposal facility, for a member of the so-called critical group, who may be exposed to external radiation, or to internal radiation through radioactive substances in the breathing air or food (Saanio et al. 2013).

Exposure of operating personnel

The exposure to radiation of personnel and other persons carrying out radiation work in the disposal facility shall be limited. Limiting the radiation exposure of personnel shall be taken into account in the design of facilities, structures and systems of the disposal facility, as well as when planning the operations in the facility.

The exposure of employees to natural radiation shall be taken into account in particular when designing the underground facilities of the disposal facility and the operations to be carried out in them (Saanio et al. 2013).

Limiting the radiation exposure of personnel

Working areas and passageways in regular use in the disposal facility shall be designed and located so that the external dose rate is low and the risk of internal exposure to radiation is small in these premises. The radiation dose rates and concentrations of radioactive substances prevailing in the different areas of the disposal facility shall be assessed. Structures, systems and equipment containing significant amounts of radioactive substances shall be placed in separate rooms or shielded effectively. Adequate safety margins shall be incorporated in the design of radiation shielding.

The areas in the disposal facility shall be classified on the basis of estimated radiation conditions. Facilities requiring radiation control shall be placed within a specified area to allow appropriate limit and control of access. In setting the protective measures and safety provisions for the underground controlled areas, the specific features concerning work in those areas can be taken into account. Such conditions and premises shall be ensured, by design and planning, for the operation, inspection and maintenance of equipment that the need for and duration of work under radiation is limited.

Devices with an alarm function shall be employed for radiation monitoring so that during the operation of the disposal facility, significant unintentional exposure to radiation will not occur (Saanio et al. 2013).

Limitation of the release of radioactive substances

The operating activities of the repositories and their structures and systems shall be planned so that the release of radioactive substances into the facilities and the environment is prevented or limited by all practical means.

Facilities where significant amounts of radioactive substances may be released shall be equipped with ventilation and filtering systems, which will:

- reduce the concentrations of radioactive substances in these facilities
- prevent the spread of radioactive substances to other parts of the facility
- restrict the release of radioactive substances into the environment.

These ventilation and filtering systems shall also be able to operate as designed during and after an anticipated operational transient or postulated accident (Saanio et al. 2013).

Monitoring radiation safety

The fulfilment of requirements concerning radiation safety during the operation of the disposal facility shall be ensured through continuous or regular measurements. The potential release routes and the environment of the facility shall in particular be subjected to monitoring.

In order to monitor the potential release routes of radioactive substances, systems shall be designed for measuring and recording data on the quantities of radioactive substances released into the environment. It shall be possible to also monitor the emissions during an anticipated operational transient or a postulated accident (Saanio et al. 2013).

Safety-related design criteria

The technical and administrative requirements and limitations necessary for ensuring the operational and long-term safety of the disposal facility shall be presented in the technical specifications. Adequate instructions shall be in place for the operation, maintenance, periodic inspections and tests of the plans, as well as for transient and accident conditions. The reliable operation of systems and components shall be ensured through maintenance and regular periodic inspections and tests. Safety related operational requirements shall be set out (Saanio et al. 2013).

Consideration of external events in planning

Impacts caused by probable natural phenomena and other events external to the facility shall be considered in the design of the repository.

The natural phenomena to be considered typically include lightning, earthquakes and floods. Other events external to the facility include electromagnetic interference, light airplane crashes, wildfires or explosions (Saanio et al. 2013).

Security and emergency arrangements

The holder of a licence for a nuclear facility shall ensure that its safety arrangements are in place. The design of security shall be based on risk analyses of the activity to be secured, and protection requirements assessed on the basis thereof. The design of security shall prepare for, among other risks, the risk of unlawful action being taken by an individual working at the nuclear facility, or by someone participating in the treatment and transport of nuclear material or nuclear waste, or by an outside group or person, who may be assisted by a person working at the facility or in a transport-related task. The design shall also account for the possibility that any person or group attempting unlawful action may have conventional weapons and explosives or those based on an electromagnetic, chemical or biological impact, as well as information and expertise unavailable to the public. Security shall be consistent with the operation, fire safety and emergency response arrangements for nuclear facility. Furthermore, security shall be consistent with the rescue service, emergency and special situational plans drawn up by the authorities.

The holder of a licence for a nuclear facility shall ensure that its emergency arrangements are in place. The planning of emergency response arrangements shall be based on analyses of the progress over time of severe accident scenarios resulting in a potential release. In such a case, variations in the state of the nuclear facility, the development of events as a function of time, the radiation situation at the facility, radioactive releases, radioactive release routes and weather conditions shall be taken into account. Planning shall take account of events reducing safety, their controllability and the severity of the consequences. Furthermore, planning shall take account of threats related to unlawful action, and the potential consequences thereof. Actions taken in an emergency situation shall be planned so that the safety of people within the nuclear facility site is ensured. Emergency response arrangements shall be consistent with the operation, fire prevention and physical protection of the nuclear facility. Furthermore, emergency response arrangements shall be compatible with the rescue and emergency plans drawn up by the authorities in preparation for a nuclear facility accident (Saanio et al. 2013).

Prevention of incidents and accidents and management of consequences

Compliance with the safety requirements concerning the undisturbed operation of the repositories shall be demonstrated by analyses and verified during the commissioning tests for the facility. The performance of safety systems designed for operational incidents and accidents shall also be, whenever practicable, tested during the commissioning of the facility.

Compliance with the safety requirements concerning anticipated operational incidents and postulated accidents shall be demonstrated with analyses that cover potential incidents and accidents of different types at the disposal facility. With regard to the representativeness of these analyses, it is essential to consider the cases which are the most limiting on the performance and dimensioning of each safety system.

Compliance with nuclear safety requirements shall be primarily demonstrated by a deterministic safety analysis. Furthermore, the technical solutions affecting the operational safety of the disposal facility shall be justified using a probabilistic risk assessment.

The potential causes for anticipated operational incidents to be considered could include at least:

- equipment failure or a malfunction with safety significance
- loss of power of a system for handling radioactive substances or of a safety system
- fire in an area or of an object significant to safety
- unexpected water leakage or flooding in the underground facility.

The potential causes for postulated accidents to be considered could include at least (Saanio et al. 2013):

- drop of a disposal canister containing spent fuel or other handling accident resulting in severe damage to the fuel
- substantial degradation of the performance of an important safety system
- explosion or rock collapse in the underground facility
- external event causing significant damage, such as a major earthquake or an aeroplane crash.

Prevention of criticality accidents

The formation of such spent fuel configurations that would cause an uncontrolled chain reaction of fission shall be prevented by means of the structural design of systems and components.

The waste canisters containing spent fuel shall be designed so that no critical fuel configurations may be formed in any operational situations, including any anticipated incident or postulated accident. The emplaced canisters shall retain their subcriticality also over the long term when the canisters' internal structures may be corroded and partly filled with groundwater. In the criticality analyses, the assumptions regarding fuel enrichment and burn-up, the safety margin for the effective multiplication factor and other factors shall be selected so that a high degree of confidence in criticality safety is achieved (Saanio et al. 2013).

Prevention of fire or explosion hazards

The disposal facility shall be designed so that the likelihood of a fire is low and its consequences are of minor importance to safety (Saanio et al. 2013).

The disposal facility shall be designed so that explosions that would jeopardise the integrity of spent fuel bundles, waste canisters/ packages, or the components or chambers containing radioactive substances, are reliably prevented.

The objective for the design of fire safety of the disposal facility shall include:

- prevention of the ignition of fires
- rapid detection and extinguishing of fires
- prevention of the propagation of fires into areas where a fire could compromise the safety of handling, storage or disposal of a canister containing spent fuel or other waste package
- minimisation of explosion hazards.

The prevention of fires and explosions in the disposal facility shall be primarily based on its layout and on the design of fire cells, which shall fulfil fire class requirement. The materials in the facility shall be predominantly incombustible and heat resistant. No materials or equipment that could increase the fire load or cause a hazard of fire ignition or explosion shall be placed within fire compartments important to safety or in their immediate vicinity. Fire compartments shall be formed for rooms or areas with significant fire load concentrations.

The disposal facility shall be equipped with an automatic fire detection system designed so that a fire can be located with sufficient accuracy. Furthermore, rooms in the disposal facility shall be equipped, as necessary, with suitable fire-fighting and initial extinguishing equipment. The fire detection and fighting systems shall be effective also during an anticipated operational transient or a postulated accident (Saanio et al. 2013).

Prevention of waste package damage

Disposal facility layout must be designed in such a way that the disposal operations, as well as excavated rock, aggregates and large transfers of equipment, are adequately separated from each other. Rock collapses and slides in rooms with waste package emplacements in progress or completed shall be prevented by keeping these rooms at a sufficient distance from excavation activities.

Installation of buffer and backfill material, must be done without damaging the engineered barrier system components in a manner that the long-term function would be endangered (Saanio et al. 2013).

Both low and intermediate level waste and high level waste are transferred via the sloping access tunnel to a dedicated repositories. These transfers need to be realized at different time.

Safety case and licensing

The National Facility, like all nuclear waste management facilities, will need to be licensed before it can start its operation. Some discussion on impact of the specific features of the National Facility on licensing and safety case is given here. The licensing process is first discussed briefly so as to see the overall role of the facility design in the process.

The National Facility will be unique in the sense that an exactly similar facility, that could act as model, does not exist anywhere today. Nevertheless, there are foreign examples of subsystem level facilities that can be utilised as analogues. The National Facility will cover all Norwegian radioactive waste management. Thus it will receive a range of wastes from different sources, e.g. hospitals, industry and nuclear research reactors. These will come in different activities, forms and shapes. This fact will emphasise the role of waste acceptance criteria (WAC) as this is the interface between waste producers and waste managers.

From waste management process point of view, the facility will cover acceptance, classification into different waste classes, subsequent treatment, packaging, interim storage and disposal. There are many waste management steps before disposal, but all pre-disposal steps must be planned taking into account the disposal needs.

In the planning of the parallel chains of operations in National Facility it is important to take disposal needs into account from the very beginning. This will probably save time, effort, and money in the long run.

The fact that the National Facility will handle all types of radioactive waste means that it is essentially a facility of facilities/repositories. Different waste categories will require different facilities (disposal solutions) including different repositories. The release barrier system for a disposal facility will be constructed following a graded approach: high-level waste requires more or a different set of barriers compared with low-level waste.

Having different co-located repositories poses a technical challenge. There is a possibility that different facilities/ repositories interact with each other and the evolution of one facility may compromise some safety functions in another repository. For instance, underground concrete structures will gradually turn the groundwater flowing through and around them alkaline, and alkaline high pH water may impair e.g. bentonite behaviour in a KBS-3 type spent fuel repository. This means that certain “respect distance” will be required. There is limited international experience in co-located disposal facilities for different waste categories, but e.g. in Finland it is currently planned a disposal facility consisting of a spent nuclear fuel (SNF) repository and a low and intermediate level waste (LILW) repository, and this experience can be used also for the National Facility.

Licensing practices for a nuclear waste management facility vary from country to country. For instance, Finland uses a stepwise approach in which a major nuclear waste management facility needs several subsequent licences (Decision-in-Principle, Construction Licence, Operating Licence, and Closure Licence). Another example is Germany in which licensing is planned to take place in one major step.

For the licensing, the facility must be shown to be safe and this is done in a Safety Case. Licence applicant prepares the safety case for the licence application. The nuclear safety authority assesses whether the safety case is of required quality. Thus, the first task of the licence applicant is to satisfy the authority’s safety requirements.

The international nuclear waste management community has discussed the role and contents of a safety case for many years in a number of expert groups. From the collaboration a common view of the main technical contents of a safety case has been developed, see e.g. Figure 2-6.

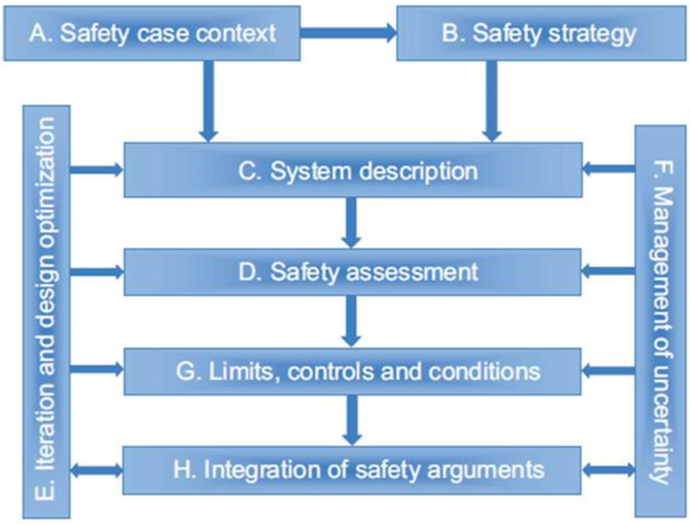

Figure 2-6. Main components of a safety case (IAEA 2012).

Looking at Figure 2-6, it is clear that the design of the facility to be licensed is extremely important. But there are other important components as well not shown clearly in the figure. One thing that has been under discussion after the Fukushima accident is the performance of organizations. This discussion has been focused on nuclear power plants, but the same logic applies for nuclear waste management facilities too. The lesson learned is that having legislation, regulations and technical preparations available is not enough. The regulations and the spirit of the regulations will have to be implemented in all different organizations. This will require good and coherent safety culture in all involved organizations. For a nuclear waste management facility this means in practice that when the competent authority reviews the safety case, it will pay attention to organizational matters in addition to technical plans and methods. In Finland, e.g., the authority will review the management system of the licence applicant (see e.g. STUK 2018).

When considering licensing a major nuclear waste management facility in a broader societal context, one finds out that the safety case, and safety argument in general, is just one argument the decision maker will have to consider, see e.g. Figure 2-7. This calls for a structured and clear safety case and communication about it so that the main points are clearly presented.

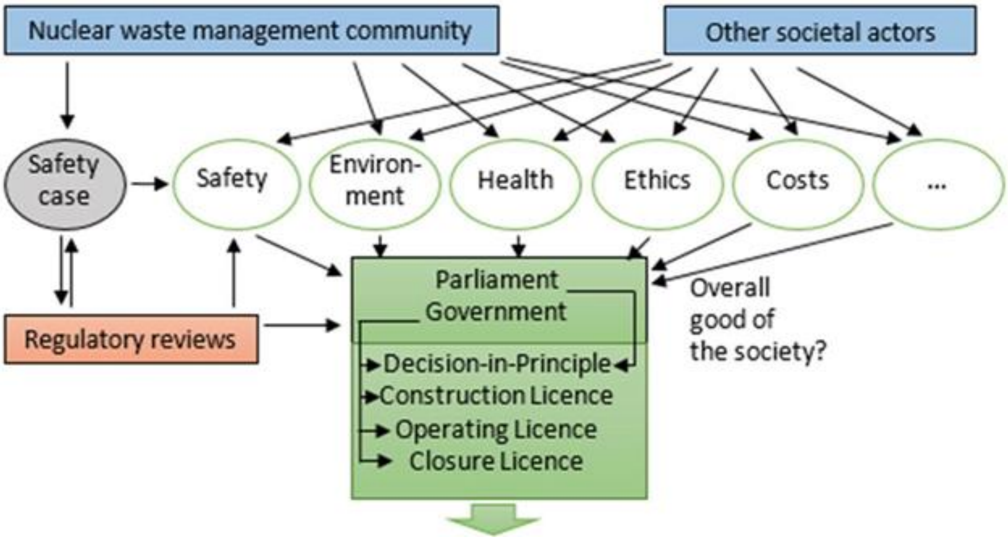

Figure 2-7. Safety case in the stepwise decision-making example from Finland (Rasilainen et al. 2019).

2.2.2 Packaging

Detailed design of packaging is out of scope of this report. Certain packaging options were chosen for purposes of this concept description of the National Facility. These are presented in the following. The concept description of the National Facility is, at this point, still flexible and able to be adjusted to different waste acceptance criteria or packaging options. The packaging options have not been analysed on a detailed level in this report.

The disposal systems chosen for the concept description of the National Facility contain the following types of packages:

1. Standard drums used for very low level and low level waste
2. Standard drums in concrete boxes used for intermediate level waste
3. KBS-3 copper canisters for spent fuel in the DGR option
4. Orano steel canisters for reprocessing scenarios (vitrified high level waste & metallic intermediate level waste)
5. BSK canister for deep borehole disposal option for spent fuel

Non-radioactive concrete and soil deposited in the landfill style repository will not be packaged.

The intermediate level waste will be packaged in concrete boxes with dimensions illustrated in Figure 2-8. In this study it was assumed that the concrete boxes would not have filling material for void space and more detailed packaging or waste processing strategies were not looked into, as details for these will also come from NND's decommissioning projects and may be further developed at a future stage. In general, treatment and packaging of the waste should provide both physical and chemical barriers to the radioactive release and void fill material depends on the design requirements and quality of host rock. Filling void space provides additional mechanical stability after corrosion has degraded the container. It may also be possible to use crushed concrete from the decommissioning waste as a fill material, but this requires further analysis.

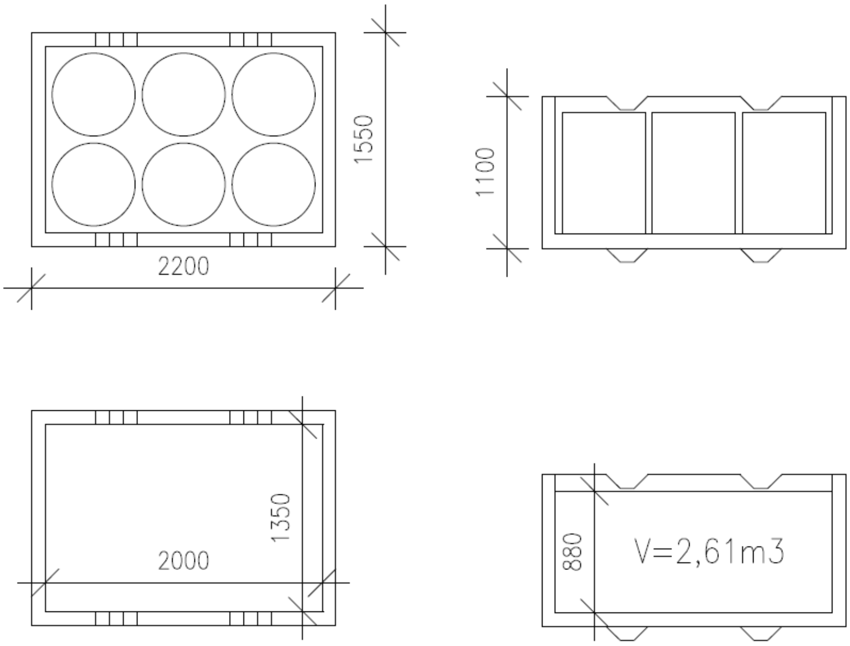

Figure 2-8. The dimensions of the concrete box in millimetres used for intermediate level waste. Figure AINS.

The standard barrel used for low and intermediate level waste is illustrated in Figure 2-9.

Figure 2-9. The standard barrel (waste drum) for low and intermediate level waste. Figure by IAEA (IAEA 1998). The dimensions are: diameter over the locking ring 613 mm, height of the drum 875 mm.

For this concept description, the spent fuel from the research rectors will be packaged in either KBS-3 style copper canisters, or, for deep borehole deposition, in BSK canisters (in the reprocessing scenario, Orano steel canisters are used for high level waste). Both Loviisa (LO) and Olkiluoto (OL) types of canisters are used as the fuel assemblies have varying dimensions. The basic scenario has 17 OL1-2 canisters and 11 LO1-2 canisters:

1. Loviisa canister outer dimensions are 1.05 m diameter and 3.55 m height
2. Olkiluoto canister outer dimensions are 1.05 m diameter and 4.75 m height

The canister inserts will need some modifications. The topic of KBS-3 canister number and the required engineering changes and modifications is described in detail in the WP1 report (Loukusa 2020) for metallic uranium. It is assumed here that the same dimensioning applies for the case of oxidized fuel since in those calculations the dimensioning was done assuming the metallic fuel would swell through oxidation reactions over time and excess volume was reserved for that purpose. However, if the oxidation route is eventually chosen as the choice for spent fuel, these calculations should be remade with more accurate information of the oxidized fuel form. The structure of the canister and insert is illustrated in Figure 2-10.

Figure 2-10. The KBS-3 canister structure with cast iron insert portraying two different canister sizes (Loviisa 1–2 (VVER-440) left and Olkiluoto 1–2 (BWR) right. Both versions of the canister have the same outer diameter of 1.050 m. The heights are 3.6 m and 4.8 m. Figure modified from Raiko (2005a).

In the reprocessing options, the high level vitrified waste or the intermediate level metallic waste will be deposited in Orano steel canisters, illustrated in Figure 2-11.

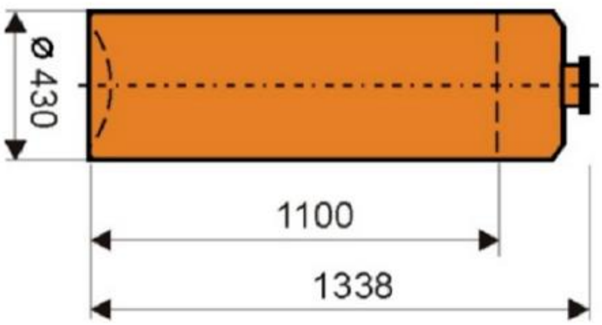

Figure 2-11. Orano steel canister (Bracke et al 2019).

For borehole disposal, several different canister designs are available. Most of the options have similar dimensions and only differentiate slightly. Most canisters have a length of roughly five metres and are either cylindrical or conical shaped. The diameter of the canisters varies from 45 cm to more than 70 cm. The most advanced waste canister is the BSK (Brennstabkokille). This canister has different modifications like the BSK-R, which has an additional unit set on the top for controlled disposal and possible retrieval operations. Figure 2-12 displays a technical drawing of BSK-R including measures for the dimension.

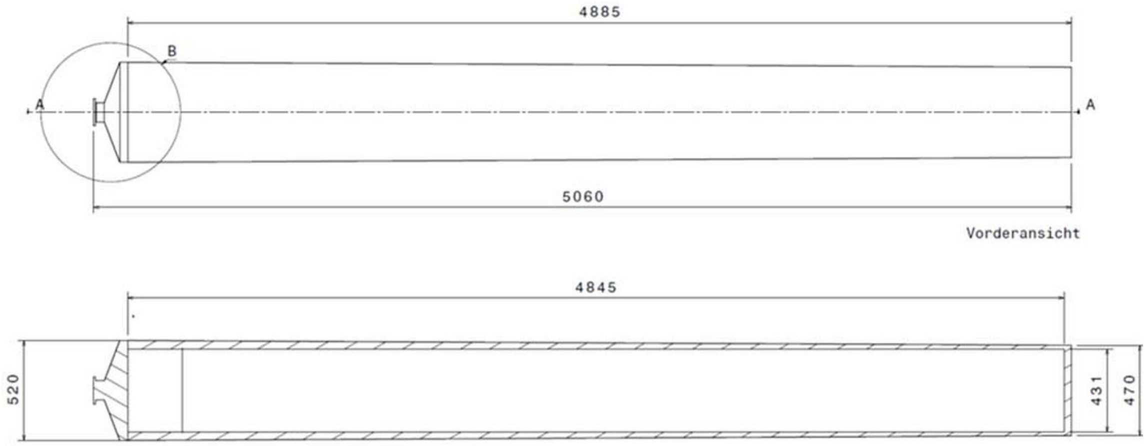

Figure 2-12. Technical drawing of the BSK-R.

Other canisters, such as the ones considered by Bracke et al. (2019), differentiate only slightly. There are also some smaller canisters, for example for reprocessed waste.

Another important aspect, which needs to be considered concerning the disposal canister, is the canister material. Many investigations and research projects (e.g. copper corrosion under expected conditions in a deep geologic repository, 2002) have shown that copper has a good corrosion resistance in deep (reducing) groundwater, which plays an important role in the long-term stability and safety of the disposal operation. In Swedish and Finnish disposal projects, copper has been the material of choice for the canisters. With this extensive knowledge, copper seems to be most suitable canister surface material for this project as well.

Pre-treating and package options for concrete are summarized in Table 2-3 Detailed evaluation of different demolition techniques and treatment options for concrete waste are outside the scope of this study and should be studied separately.

Table 2-3. Concrete pre-treating options and use of packages with evaluation of pros and cons of these methods.

Pre-treating option and use of packages	**Pros**	**Cons**
Crushing of concrete into fractions	+ Common method after demolition of concrete structures + Easy handling + Possibility to homogenise the waste streams in case contamination of the concrete from air pollution or by radionuclides (hot spots) + Possibility of recovery of the material (e.g. as a backfill material) + Temporary storage e.g. in silos possible.	- Larger surface area in crushed concrete in comparison to large concrete blocks. This may have effect on the dissolution of substances and radionuclides from the concrete - Dusting when processing and handling (there might be a need to avoid this due to operational safety or environmental reasons) - Some fractions cannot be used as backfill material and may need to be deposited in any case. For example, if there is excess of fine fraction in the material.
Crushing of concrete and stabilization with cement (~30 V-% cement)	+ Reduces dissolution of contaminants and radionuclides + Stabilizes the waste. + Mixing in concrete station and pumping into the repository possible. + Possibly long curing time.	- Dusting of crushed concrete - Curing time – requires additional time to harden - Additional CO_2 emissions from cement. - Costs for cement - Effect on waste volume if packages or moulds are not used (friction angle) - Need for moulds at emplacement?
Concrete blocks	+ Limited amount of dusting depending on the demolishing method selected. + Lower solubility of substances in comparison to crushed concrete.	- Varying block size and shape increases the required space for disposal (calculated for examples with void volume 5-30%). - Poor stability of the emplaced blocks at installation if no packages are used (operational safety issue). - Handling and storage may be more difficult than in crushed concrete option.
Packages (e.g. open top 20´shipping containers with capacity of 33 m^3, L 12 m, W 2.4 m and H 2.6 m.)	+ Handling + Can be equipped with lids (water proof sealing) + Can be used as storage of materials + Traceability and tracking of the waste (e.g. with RF-ID). + Waste packages can be placed on top of each other with good stability. + Metal packages may increase the public acceptability of the landfill repository.	- Costs - Additional CO_2 emissions - Metal packages not needed from radiation safety point of view. - Corrosion of the packages and leaching into groundwater.

The non-radioactive concrete and soil will be deposited in 20´ open top ISO shipping containers (L 12 m, W 2.4 m and H 2.6 m) where the dimensioning factor is the maximum bearing capacity of the containers (28 t).

2.2.3 Waste inventory

The waste inventory for the National Facility consists of the following types of waste:

- Decommissioning waste from the research reactor facilities, including spent fuel,
- Legacy waste that does not meet waste acceptance criteria of Himdalen repository,
- Radioactive waste generated in civil use over the 100 years following the commissioning of the National Facility.

The waste is categorized by activity into non-radioactive (NRW) (i.e. below the free release limit), low level waste (LLW), including also very low level waste (VLLW), intermediate level (ILW) and high level waste (HLW). The total amounts of waste in each category are given in Table 2-4. This data is derived from the two reports by Studsvik (2019), where in Tables D-14 and D-15 the amount of waste in standard barrels for landfill repository is given as approximately 41,000 barrels and ILW as approximately 8,000 barrels. However, it should be noted that in the Studsvik reports the waste in landfill category is VLLW or possibly contaminated waste, which in this report is deposited in the intermediate depth repository and only non-radioactive waste is deposited in the landfill repository.

The number of KBS-3 canisters was calculated as part of this project and the calculations as well as a more in-depth description of the spent fuel inventory are reported by Loukusa (2020). It should be noted that several different scenarios were considered and the number of canisters depends on the level of engineering and manufacturing changes that are required to the canister and insert. The number 28 (“Option C” in the report) is therefore taken as a first approach in this report and is a subject that should be investigated more closely in future. The option corresponding to 28 canisters uses multiple assemblies placed in each opening of as-fabricated cast iron inserts, and “layered” canisters are used for shorter fuel assemblies. This option was chosen based on the ability to use existing insert design as opposed to having to design, manufacture and test a special design for National Facility.

The amounts of decommissioning waste are based on two reports by Studsvik (2019). The amounts for legacy and civil waste were given by NND.

Table 2-4. Inventory data used for the design basis of the National Facility. The concrete packages referred to in the table are the packages described in the previous section and the standard barrels have a volume of 200 litres. This table lists the values for the base case (oxidised fuel). The values for LLW and ILW barrels and concrete packages are numbers for either barrels or packages. This estimation should be improved in later phases of the project as waste acceptance criteria and inventory data are better known.

Spent fuel				
	28 KBS-3 canisters (16.5 tons)			
Decommissioning waste				
	Tons	Cubic metres	Standard barrels	Concrete packages
NRW	33462	13743	N/A	N/A
LLW	13890	8500	41000	3257
ILW	2036	1600	8000	1333
Other (legacy waste)				
			Standard barrels	Concrete packages
		60	300	50
Civil waste (generated over the 100 years following the commissioning of the National Facility**)**				
		Cubic metres	Standard barrels	Concrete packages
LLW		2105	10000	807
Total				
	Tons	Cubic metres		**Packages**
Spent fuel				28 canisters
NRW (concrete, soil)	33462	13743		1165 containers
To VLLW/LLW repository		10605		51000 barrels
To ILW repository		1600		1383 boxes

For the non-radioactive concrete and soil, the number for containers is given in Table 2-5.

Table 2-5. The volume of deposited concrete and soil waste depending on the pre-treating option selected. For packing in an ISO 20' shipping container, the dimensioning factor is the weight of the waste.

Number of shipping containers needed			
Container (open top shipping container 20´)	m (t)		V (m^3)
Outer volume			38
Maximum capacity (inner volume)			33
Maximum capacity (tonnes)	28		
Amount of containers needed	m (t)	V (m^3)	**Number of containers**
Total mass to be deposited	32613		**1165**
Total volume of containers		**44572**	

In addition to this "base case" scenario, alternative waste inventories are also considered based on spent fuel treatment options. The scenarios are thus as follows:

- Base case, Oxidation: metallic uranium is treated with oxidation method and deposited in KBS-3 canisters.
- "No treatment for spent fuel" option: metallic uranium fuel is directly deposited in KBS-3 canisters. Not expected to change canister number or affect the inventory volume significantly, so the number of canisters is assumed to be the same as in the base case, see Table 2-4.
- Spent fuel reprocessing options: two options for spent fuel reprocessing exist that correspond to different impacts on inventory.
  - High level vitrified waste − eight Orano canisters
  - Intermediate level metallic waste − 500 Orano canisters

For the latter alternative scenarios (reprocessing options), the total waste inventories are listed in Table 2-6 and Table 2-7 below:

Table 2-6. Waste inventory for the high level vitrified waste scenario.

Total			
	Tons	Cubic metres	Orano canisters
Spent fuel			8
NRW (concrete, soil)	33462	13743	1165 containers
To VLLW/LLW repository		10605	51000 barrels
To ILW repository		1600	1383 boxes

Table 2-7. Waste inventory for the ILW compacted metallic waste scenario.

Total			
	Tons	Cubic metres	Orano canisters
Metallic ILW	277.5	100	500
NRW (concrete, soil)	33462	13743	1165 containers
To VLLW/LLW repository		10605	51000 barrels
To ILW repository		1600	1383 boxes

Additionally, there may be some mining waste (4500 tons / 2500 cubic metres) from Søve mines that may be deposited in the landfill repository of the National Facility. This waste is not included in the design basis for the repository, but the option to increase the dimensions of the landfill repository is considered as an alternative scenario.

2.2.4 General schedule

The National Facility is planned to operate for 100 years. Figure 2-13 illustrates the general schedule for planning, licensing and construction of the facility. It is noted that the schedule is fairly optimistic. In many waste management programmes, site selection has been a challenging step to complete and could potentially lengthen the process also in Norway compared with the timetable in Figure 2-13.

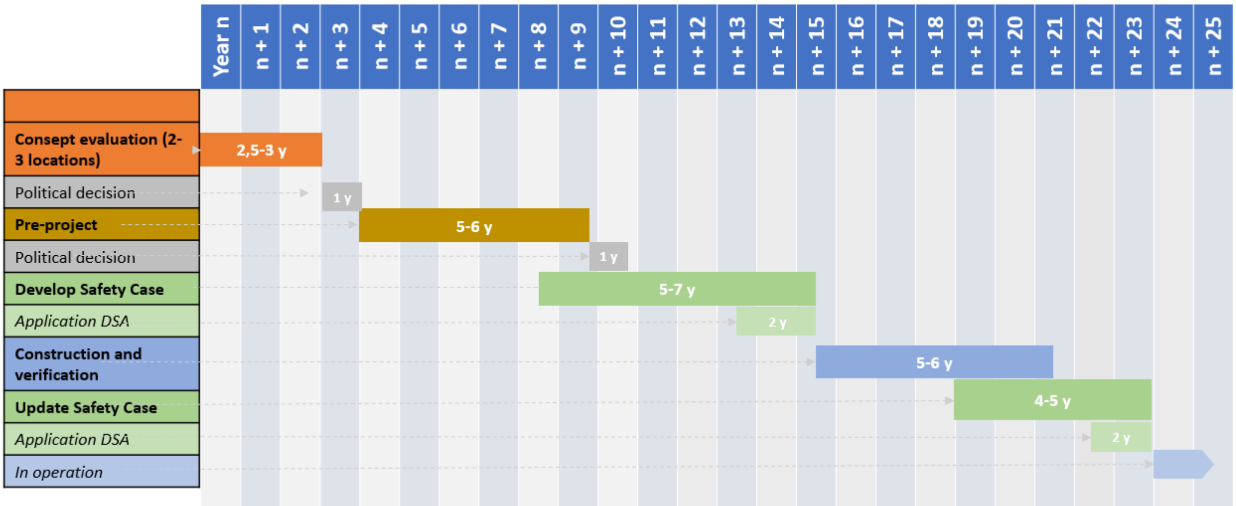

Figure 2-13. The general schedule for planning, construction and commissioning of the National Facility. "Year n" is currently planned to be 2023. Source: NND.

2.2.5 Radioactive waste produced in the packaging plant

There may be some minor amounts of radioactive waste produced in the on-site packaging plant for low and intermediate level waste, but these are not considered to be significant at this concept description stage. It should be noted that this is assuming that spent fuel will not be packaged on-site but in some other, existing facility. If this plan were to fail and an encapsulation plant for high level waste was required at the National facility, this estimate will need to be reconsidered.

The last phase in the life cycle of the packaging plant, decommissioning, also produces radioactive waste. That is not included in the scope of this study.

2.2.6 Layout flexibility and constraints

The design requirements emphasise the importance of flexibility in space allocation to allow possible changes that may be caused by, for example, bedrock conditions, the amount of waste to be disposed of, or changes in time schedules (Saanio et al. 2013).

The need to ensure the sufficient cooling of canisters has an impact on the geometry of the HLW repository options. The chemical stability of bentonite shall be ensured for a very long period of time in order to guarantee the long-term safety of the HLW disposal solution. For this reason, the temperature of canisters and the surrounding interface with bentonite shall be restricted so that it does not exceed +100 ºC for DGR case. In order to provide the basis for temperature calculations during the research phase, the thermal properties (thermal conductivity, heat capacity, possible anisotropy of properties) of the local bedrock in the actual disposal site are studied.

Temperature dimensioning is applied to adjust the locations of HLW deposition tunnels and canister positions so that excessive warming up cannot occur. Also, gaps between operational periods in disposal activity may affect the temperatures of the bedrock mass. In addition, the warming of the rock produces increased stresses in the rock. Rock mechanical engineering will ensure that the bedrock of the HLW repository can endure different combinations of loads.

The engineered release barriers shall be effective in preventing the release of disposed radioactive materials into the bedrock. The characteristics of the bedrock in the disposal site shall, as a whole, be favourable for isolating radioactive substances from living nature.

The methods used for the construction, operation and sealing off repositories and other underground openings shall be chosen so that the bedrock will maintain its natural containment characteristics in an optimal fashion. The migration of materials detrimental to long-term safety, such as organic matter and oxidising agents, shall be minimised. The above matters shall be taken into account when planning, designing and constructing the disposal facility.

The planned disposal depths shall have sufficiently large and unfractured rock volumes that are suitable for the construction of repositories. The properties of bedrock in the planned disposal site shall be established through studies carried out at the planned disposal depths in order to provide the necessary information for planning and designing the repositories and for producing the safety assessment.

The layout, excavation, construction and closure of underground facilities shall be so implemented that the bedrock will maintain the properties important to long-term safety.

A research, testing and monitoring programme, which will ensure the suitability of the rock for disposal, define important bedrock characteristics concerning the safety aspects and ensure the long-term performance of the release barriers, will be implemented during planning/siting, construction and operation of the disposal facility. This programme (Saanio et al. 2013) typically includes at least:

- investigation into the properties of bedrock blocks to be excavated
- monitoring of stresses, movements and transformations of bedrock surrounding the repositories
- monitoring hydrogeology surrounding the repositories
- monitoring groundwater chemistry at the facility site
- monitoring the behaviour of the engineered barriers.

A provision shall be made for a potential change in the underground facility plan in the case that the quality of the rock surrounding the planned repositories proves to be significantly less favourable than the design basis. In order to maintain the bedrock properties that are favourable to long-term safety, the following (Saanio et al. 2013) shall be taken into account:

- one selection criteria for the excavation methods to be used is that of limiting the excavation disturbances to the bedrock surrounding the repositories
- the reinforcement and sealing of bedrock shall be carried out in such a manner that no significant quantities of materials harmful to the performance of release barriers enter the repositories
- the migration of organic and oxidising matter to the repositories shall be minimised

- the repository openings shall be backfilled and sealed off immediately when the disposal operations and associated monitoring operations allow.

2.2.7 Implementation in phases

The implementation of disposal, as a whole, shall be planned with due regard to safety. The planning shall take account of the set time frame and the utilisation of the best available technology and scientific knowledge.

Subsequent to the planning/siting, implementation of disposal facility includes the following phases:

- construction and operation of an underground demonstration openings and other necessary research, development, (cold) testing and planning work (the site confirmation for a detailed repository design and safety assessment include characterisation and demonstration performed underground in e.g. Sweden and Finland)
- encapsulation and packaging outside the (National) disposal facility and construction of the rest of the disposal facility
- transfer of waste canisters and packages into their deposition positions and installation of buffer and backfill materials
- closure of emplacement rooms and other underground openings
- post-closure monitoring, if required.

These phases, which can be partly parallel, shall be scheduled and implemented with due regard to long-term safety. In doing so, the following aspects (Saanio et al. 2013), among others, are considered:

- reduction of the activity and heat generation in waste prior to disposal
- introduction of the best available technique or a technique that is becoming available
- acquisition of adequate experimental knowledge of the disposal site and other factors affecting long-term safety
- potential surveillance actions related to ensuring the long-term safety or to non-proliferation of nuclear materials
- aim of preserving the natural features of the host rock and other favourable conditions in the repositories
- aim of limiting the hazards and other burdens to future generations due to long-term storage of waste.

An appropriate quality system is deployed in implementing the disposal and its associated research and development work and safety assessments, and it is extended to all organisations having a material impact on the long-term safety of the disposal project.

Construction and operation stages

During the construction and closure of the repository, efforts are made to maintain the bedrock's original properties and to keep changes in as limited an area as possible around the tunnels and shafts. Accordingly, the rock is excavated carefully so as to keep the impact on the surrounding bedrock at an insignificant level. Water leaks can be limited by avoiding water-bearing structures and by sealing leaking points using, for example, grouting.

Operation of the disposal facility shall not cause any radiation exposure endangering the health of facility personnel or other people or cause any other damage to the environment or property.

In order to ensure the safe operation and long-term safety of the disposal facility, for the design, construction and operation of the facility as well as for the sealing of the facility:

- proven or otherwise carefully examined high quality technology shall be employed
- advanced quality assurance programmes shall be applied
- an advanced safety culture shall be maintained.

The experience obtained in operating the disposal facility shall be systematically monitored and assessed. Actions for improving safety, justifiable on the basis of operating experience and safety reviews as well as the advances in science and technology, shall be taken.

The performance of release barriers shall be monitored during the operating phase in order to ensure their compliance with the plan (Saanio et al. 2013).

Closing stage

The migration of materials detrimental to long-term safety, such as organic matter and oxidising agents, shall be minimised. All structures and systems utilised during operation will be dismantled from the underground facilities. The backfilling of facilities and construction of sealing structures will begin simultaneously with the dismantling work. The facilities located at the disposal depths and the vertical shafts will be backfilled. The upper parts of the shafts and the access tunnel will be closed with concrete structures (Saanio et al. 2013).

Post-closure period

Disposal shall be planned so that no monitoring of the disposal site is required for ensuring long-term safety after closure.

On the basis of primary records and verification measurements, adequate inventory data of the nuclear materials and nuclear wastes to be disposed of shall be obtained during the operational period of the disposal facility for long-term deposition. The disposal facility shall be designed so that, in the post-closure period, it is feasible to implement arrangements for discovering and precluding actions on the repository which would jeopardise long-term safety or involve breach of the treaties concerning the security of nuclear materials.

The disposal concept is designed so that there will be no need for monitoring or other maintenance after the closure of connections to the repositories. If desired, signs can be left on the site to indicate the presence of radioactive waste underground (Saanio et al. 2013).

2.2.8 Safeguards of nuclear materials

Safeguards of nuclear materials shall be taken into account in the design of the disposal facility. The transfer routes, canister stores, handling processes and the safeguard measures for nuclear materials shall be designed and planned so that the continuation of knowledge is assured at every step. Safeguards of material flows in and out of the underground rooms shall be feasible. The fuel elements and canisters shall be identifiable (Saanio et al. 2013). The safeguard requirement does not apply to VLLW, LLW and ILW in this respect.

The aim of the nuclear material safeguards in the disposal facility is also to ensure that the facility, especially in its underground part, has no rooms, materials or operations outside the system of nuclear material accounting and that the waste canisters remain in their declared positions during the operation and after the closure of the facility (Saanio et al. 2013).

2.2.9 Management of requirements

A requirements management system shall be created to define, document and administer the setting of requirements originating from different sources (such as public authorities, technology, owners) on long-term safety of the different components and structures of the release barriers in the repositories (Saanio et al. 2013). The requirements regarding system components such as canisters, waste packages, buffers and structures of the repositories (e.g. the deposition holes, deposition tunnels) will be defined in the requirement database by appropriate references to and interdependencies with other requirements. The requirement management system will contain, for example, the design specifications and variation ranges of conditions where the system shall function as planned.

A rock classification system needs to be created for defining the desired properties for host rock material and for developing the acceptance criteria regarding the suitability of any given host rock volume for disposal purposes, including the acceptance criteria for deposition holes and tunnels.

The applicable classification system/criteria will cover the aspects of both long-term safety and suitability for construction. By applying the criteria, the conditions to be expected near the deposition holes and tunnels become more predictable, as do the probabilities of deviations and disturbances.

2.2.10 Waste flows

The National Facility is expected to have waste flows of non-radioactive waste, very low, low and intermediate level waste and high level waste (either spent fuel or vitrified waste from reprocessing; see the different scenarios in Section 2.2.3). The main waste flows are illustrated in Figure 2-14.

Non-radioactive waste (mainly concrete from decommissioning activities) is transported to the site in large containers and deposited to the landfill repository. The waste will not be packaged or put into intermediate storage at the National Facility.

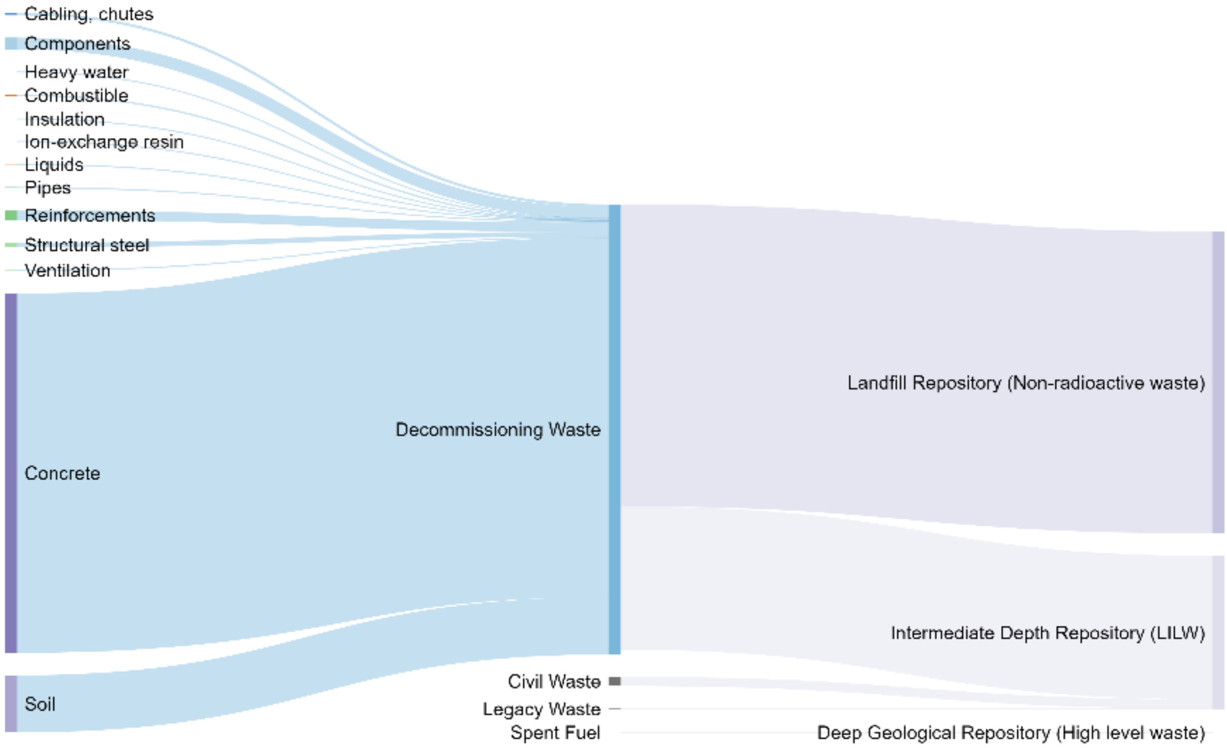

Figure 2-14. The main radioactive waste flows of the National Facility, by mass. The vast majority of waste is decommissioning waste and specifically non-radioactive concrete (approximately 47,000 tons) and soil (approximately 6000 tons).

2.2.11 Environmental impact factors

In this section, typical environmental impact factors are listed and they have been regarded when possible in this very early conceptual phase. Typical environmental impact factors of disposal facilities are listed as following:

Impact on nature and natural resources

Impact on air:

- excavation dust
- traffic emissions

Impact on water:

- groundwater table
- drainage water led to a nearby water system
- oil spills
- earth moving work and asphalting effect on the absorption of the surface water

Impact on organic nature:

- utilized areas change the current state of the site
- blasting vibration, dust and noise
- traffic noise
- ventilation building equipment noise

Impact on utilization of natural resources

- recreational use of the site
- restriction by authorities for security, monitoring and ore mining

Impact on land use, cultural heritage, the landscape, buildings and the urban image

Impact on current land use of the site

- regional and community planning
- land ownership

Impact on cultural heritage, buildings, the landscape and the urban image

- valuable buildings, areas or sites
- changes in landscape and views to site area

Health effects of radiation

- transfer of nuclear waste (including accident situations)
- operation of the National Facility (in normal, malfunction and accident situations)
- post closure phase (basic case, scenarios)

Other effects on human health

- traffic emissions and noise
- ventilation building equipment noise
- excavation noise, dust and vibration
- traffic accidents

Psychosocial effects

- emotional reactions
- stress management
- societal movements
- fears and anxieties

Social impacts

- business activity
- agriculture
- tourism
- population size and structure
- other community structure and infrastructure
- property values
- municipal economy
- living conditions and general wellbeing

3 NATIONAL FACILITY COMPLEX AND OVERALL SCHEDULE

Facility complex

The National Facility is, in this work, assumed to be situated on an illustrative site, which has existing infrastructure connections (roads, electricity network, sewage, water supply, district heating, explosive storage and supply etc.) at place. The site has surface facilities above the underground repositories and openings built in crystalline rock.

Waste halls at the -100 metres level intermediate depth are called *intermediate depth repository* for VLLW, LLW and ILW. Connections to the ground level from this disposal level are via the access tunnel running at a slope of 1:10, and via three vertical shafts. A personnel shaft reaches the repository depth of 100 metres. Inlet and exhaust air shafts reach the depth of 100 metres or, if the DGR is constructed, all the way to the depth of 400 metres.

Before the possible construction of the DGR and the commencement of related disposal operations, it is assumed that an underground demonstration opening will be constructed at the facility site at the depth of 400 metres. DGR consists of a spiral-shaped access tunnel and inlet and exhaust air shafts as well as auxiliary rooms at the bottom of the shafts.

The underground part of the disposal facility consists of connections from the surface level to the *repository levels of -100 and possible -400 metres*, auxiliary rooms and actual repositories. Two deposition tunnels and deposition holes drilled in their floors are collectively called the *deep geological repository* for HLW. An alternative for that is a *deep borehole repository* with one borehole of a few thousand metres depth with the canister disposal zone in its lower part.

A *ventilation building* will be constructed at the top end of the inlet and exhaust air shafts and *operation building* for later use for personnel shaft reaching the intermediate depth level (100 m). A *tunnel portal building* for the technical systems of the access tunnel will also be needed. For the operation, a *packaging plant* for VLLW, LLW and ILW from medicine, research, industry etc. and a *waste reception building* are also needed. Waste reception building is first for HLW, then for ILW and finally for VLLW and LLW receive control, contamination test, transfer from road transportation equipment to canister/waste transfer vehicle and temporary storage.

Some other auxiliary buildings and structures are also needed. Examples of these are a maintenance and storage hall, storage/construction area, refuelling station and a so-called research building for the research equipment and personnel. If a deep borehole repository will be constructed, an area with an *emplacement building* for the borehole activities is also reserved. *Office building* and *visitor centre* are located outside the facility fence. An option for a *landfill repository* concept with temporary container laydown area is also designed above the ground level.

Figure 3-1 and Figure 3-2 illustrate examples of placement of all nuclear waste from Norway within the National Facility. Chapters 6 to 8 contain a detailed description of the underground parts of the disposal facility.

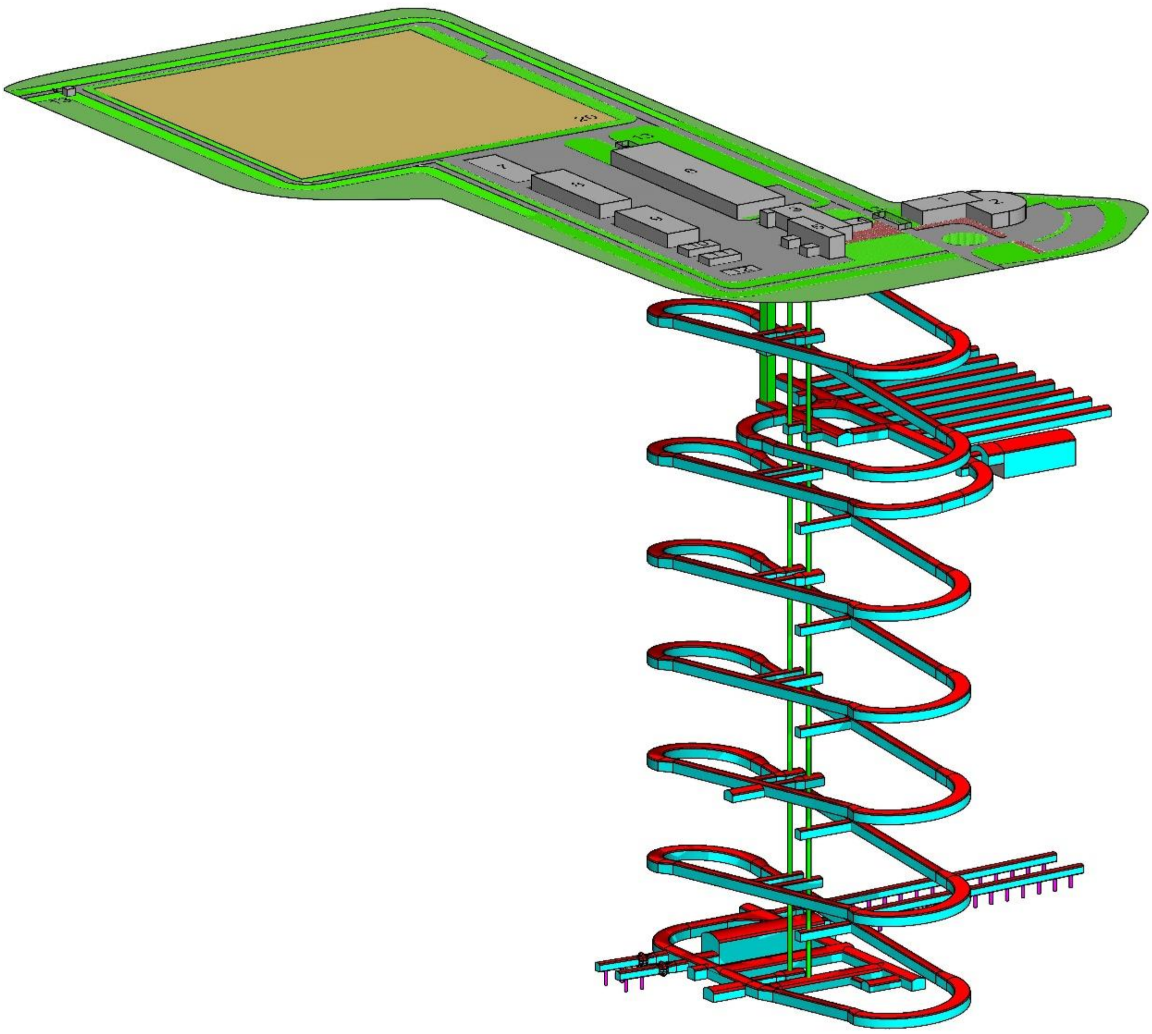

Figure 3-1. Illustration of the National Facility if DGR is used for HLW disposal. Figure 5-5 lists the names and indexes of the different buildings. Figure AINS.

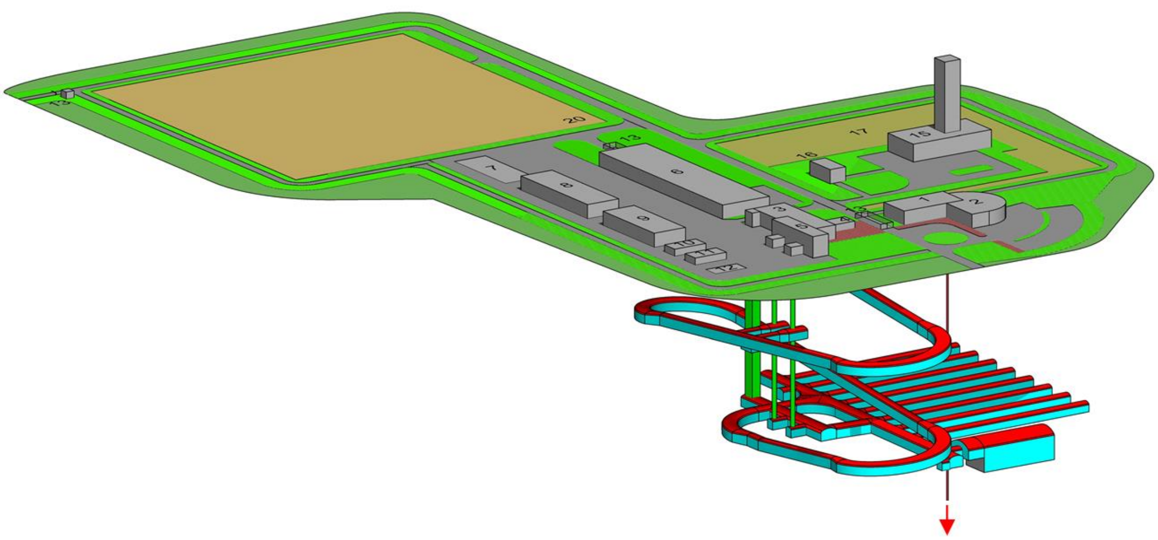

Figure 3-2. Illustration of the National Facility if deep borehole is used for HLW disposal. The borehole is the thin black line below building 15, and it continues out of the figure with red arrow. Figure AINS.

Overall schedule

According to the general schedule for the National Facility, it is assumed that around 25 years are needed for preparations, construction and licensing of the facility (Figure 2-13). Preparations include e.g. political decisions, development of the concept and safety case. After construction and testing, the operation can start. Start of the operation is assumed for 2050, Figure 3-3.

Operations will start by disposing of the spent fuel either in the deep geological repository or in the deep borehole repository. This operation will take roughly 2 years.

Non-radioactive waste will be emplaced to the landfill repository or possibly in lower parts of the National Facility as part of backfill material if the deep geological repository is chosen for the disposal of the spent fuel. In this case some of the openings between -100 m and -400 m levels could be backfilled with the non-radioactive waste. Deposition of the non-radioactive waste will be done after disposal of the spent fuel and will take a couple of years. Without the DGR, most of the non-radioactive waste should be stored for 100 years before using it as a closure material for intermediate depth repository: that is not reasonable because of harmful organic material could intrude to the waste during the storing period.

The next phase in the overall schedule is the disposal of decommissioning and legacy waste. The emplacement of existing decommissioning and legacy waste will take roughly three years. After that the disposal of waste from different sources, e.g. hospitals and industry can be started. This can be done in campaigns that will be defined and decided later or always when more waste is accumulated.

When all waste is disposed, closure of the National Facility can start. All the underground openings are backfilled and plugged and above ground structures can be removed. This will take couple of years.

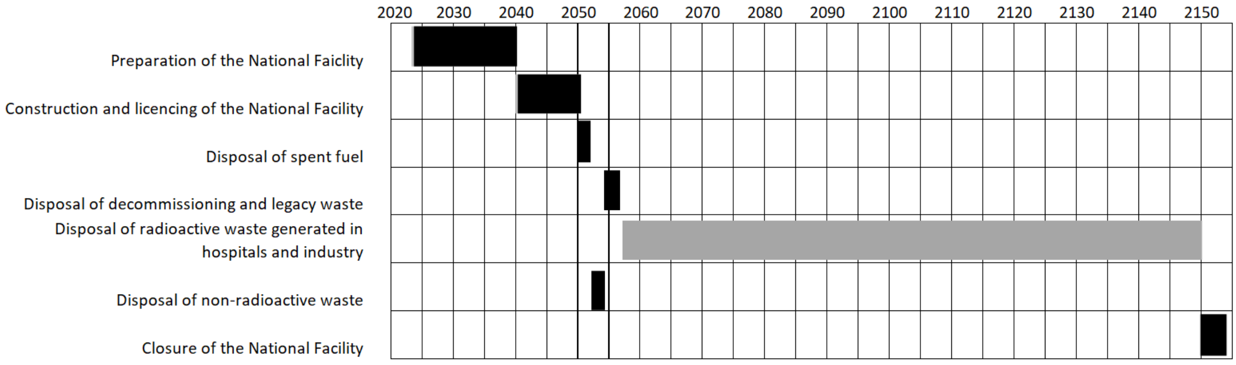

Figure 3-3. Overall schedule. Figure AINS.

4 SITE SELECTION

4.1 General

A key component in the development of disposal of radioactive waste is to find, investigate and select a geological environment and a site where a safe and efficient facility can be built. This involves acquiring sufficient environmental, geological, geotechnical etc. information to be able to perform an assessment of the possibilities to construct a facility and to perform safety and environmental impact assessments. Siting of a disposal facility can turn out to be controversial from a public acceptance point of view. It is important to connect a public consultation and information to the siting programme. Local acceptance of the disposal facility is considered to be of paramount importance. There are several examples where the siting failed due to public opposition. These national nuclear waste management programmes had to be restarted from the very beginning, which then introduced decade long delays to the original plan. Canada, Germany and UK are prime examples of a failed site selection process for HLW disposal. All of them have since then restarted their site selection process, but none has selected a disposal site yet (as of 2020).

The approach to site selection varies by country based on nation-specific requirements and environmental factors. However, site selection is a critical phase of the lifetime of any radioactive waste management programme. It has a bearing on the long-term safety of the disposal system. Identifying a suitable site requires a systematic approach.

Considering the characteristic of radioactive waste to be disposed of in Norway and the limited volumes of the waste streams, it seems to be highly inefficient to look for comprehensive solutions that involve more than one disposal site. A national solution for Norway should, therefore, allow to concentrate the vast majority or all activities in regard to the radioactive waste disposal at one site. Of course, such a general decision will depend on the availability of sites that fulfil all requirements. Accordingly, this aspect will be very important for evaluating potential sites for a certain disposal solution. In the following, benefits and potential disadvantages of a single disposal facility site are presented. It should be noted that the listing does not take into account the relative importance of each point. Also, each of the item would have different weighting of the benefit/disadvantage for each separate disposal system.

Benefits of a single disposal facility site:

- One licence (considerable time, effort, cost) for each stage of facility development (site selection, construction, trial/routine operation, closure, institutional control, release from institutional control),
- One site selection / investigation process (cost, effort),
- Shared land procurement and infrastructural cost,
- Shared construction cost for intermediate depth facility and DGR results in considerable savings (little effect on the deep borehole disposal)
- Shared construction cost for surface facilities - admin/technical/support facilities for all disposal concepts in single site: buildings, other surface facilities, utility connection etc.
- Operation (disposal): shared administrative personnel (including visitor centre etc.), security, monitoring, at least partly the same staff could be used for different disposal operations
- Closure – for shared intermediate depth facility and DGR considerable savings (little effect on the deep borehole disposal of HLW)
- Long-term operations in single location: security, monitoring, maintenance.

Disadvantages:

- Additional requirements for the site might complicate site selection (reduced number of suitable sites),
- Individual site for HLW: higher activity of waste, but surface lifetime of facility very short,
- Individual site for LILW: less activity compared with HLW,
- Individual site for landfill: long surface lifetime, maybe with institutional control, but practically no activity.

4.2 Site selection process and criteria

Site selection process is usually performed stepwise, starting with a wide search across the country. In the next step, a few areas are investigated in more detail, including geological and other investigations from the surface and possibly with boreholes. In the selection of these areas also the aspect of public acceptance is taken into account. Finally, one or a few sites are further investigated to such a detail that a comprehensive safety assessment can be performed. In parallel with the site investigations, social studies and public consultations might be performed as well as an information programme to ensure that the public concerned can be well informed and informed decisions are made.

The siting process includes site investigation plans that are developed for regional and site-specific locations. Site investigations consist of a broad range of geoscientific activities to acquire geoscientific information relevant to the safety case and engineering. Site investigations provide information for conceptual models of the natural systems, engineered system and for coupled processes, and for the biosphere.

The disposal system design proceeds to the preliminary design and to more detailed design during the siting phase. Research and development on the engineering design components, including waste packages, construction methods, buffer systems, and emplacement methods are conducted in parallel with the site investigations.

Siting is the process of surveying and selecting a suitable site for the disposal of radioactive waste. The siting process consists of a series of related activities with the objective of selecting suitable sites for a new nuclear installation, in this case a disposal facility. The process systematically and successively applies a number of screening criteria to screen out those sites with attributes which contribute unfavourably to the safety of the facility.

The siting process has often three distinct steps starting with the region(s) of interest as given.

- (1) Regional analysis: This is the first step, in which region(s) of interest are analysed to identify potential sites. All potential sites in a region should be taken to the next step (screening) unless their exclusion can be appropriately justified.
- (2) Screening: In the second step, the potential sites are screened to choose the candidate sites. The principal objective of this step is to exclude unfavourable sites on the basis of both safety related considerations and non-safety-related considerations.
- (3) Evaluation, comparison and ranking: The purpose of the third step is two-fold:
    - (i) to evaluate the sites in order to ensure that there are no features (at the sites or in their surrounding areas) that would preclude the construction and operation of the nuclear installation, and
    - (ii) to compare the candidate sites and to rank them in order of their attractiveness as possible sites for a nuclear installation.

Information on the implementation of the selection process of sites for geological disposal is provided in publications of IAEA (1994), Arnold et al. (2010, 2013) and Freeze et al. (2014). Characteristics of acceptable sites for near surface disposal are described in, for example, IAEA (1999, WS-R-1, chapter 6) and IAEA (2001, chapter 2.4.4). Siting of near-surface facilities is also described in IAEA (1994).

Siting work relies on expertise from a wide range of disciplines. These include, for example, geosciences (structural geologist, hydrochemists, rock mechanical experts, geophysicists) and socio-political experts.

Siting criteria are the factors that are applied to potential sites to exclude or rank them. The siting criteria will support the main objectives of the site selection programme as to find out if:

- a safe disposal facility could be developed on the site,
- the site would keep long-term radionuclide releases within a regulatory limit,
- it is technically feasible to build the facility on the site,
- the facility would be environmentally acceptable during both construction, operation and post-closure,
- the development of a facility on the site would have a public acceptability, and

- the cost of the disposal facility would not be prohibitive for the project.

Each national programme develops detailed siting criteria and weighting around these topics based on country-specific issues (political environment, legislative requirement and so forth). For example, in some countries social acceptance or land usage might have lesser impact compared with, for example, the total cost of the facility development.

The development of the specific siting process and siting criteria for the national facility in Norway is out of scope of this report. Figure 4-1 provides an illustration of site selection scopes from Finland and Sweden.

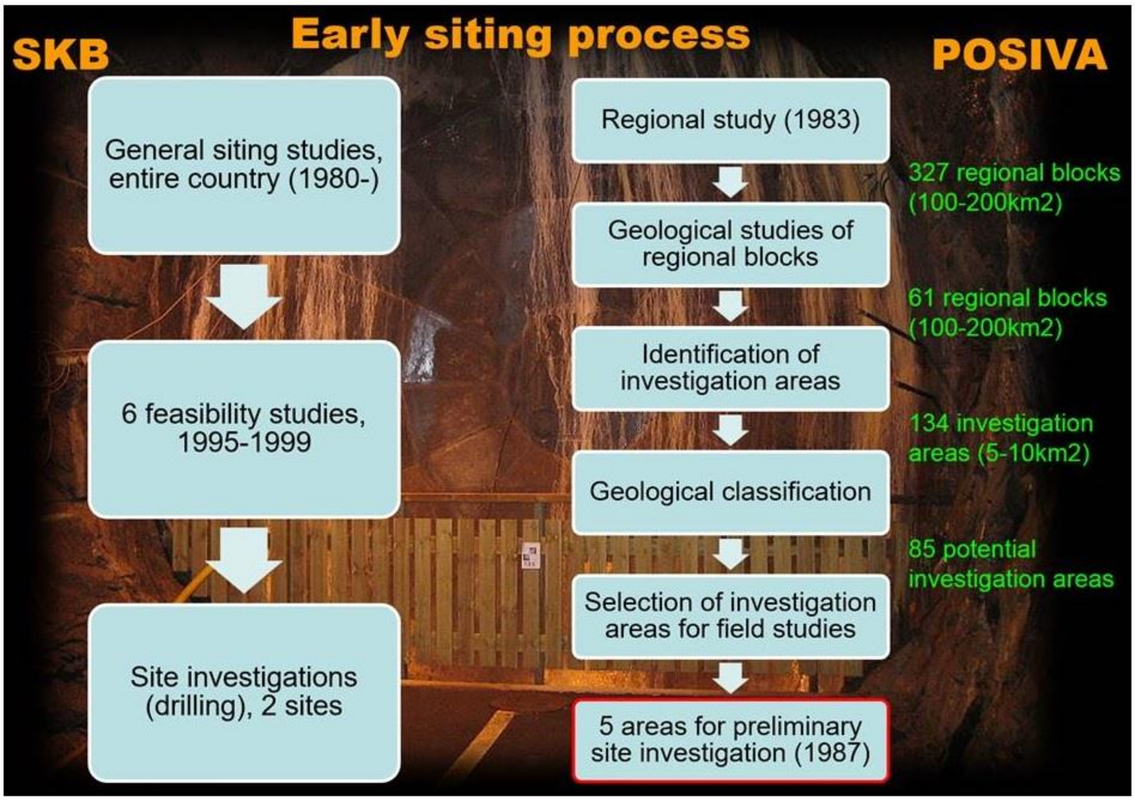

Figure 4-1. Visual depiction of site selection scopes in Finland (Posiva) and Sweden (SKB).

4.3 Site characterisation activities

Site characterisation work is carried out to gather data to support the site selection process. The investigation activities are developed and planned in parallel with the development of the siting process. Site investigation, or site characterisation, follows a similar stepwise manner as the siting process from generic desktop studies to detailed site characterisation investigations. In larger disposal facility programmes, investigations start with generalised desktop studies of several sites and moves forward to more detailed studies with less sites. At the end of each stage, a subset of sites is carried forward and more detailed site investigations are conducted within each subsequent stage. The aim is to use information, mainly geological, to screen areas suitable for further studies.

In Norway, the site investigation plan follows the siting process, which may omit the approach of having multiple sites in the beginning. This is a strategy decision that is taken at the beginning of the siting process. Nevertheless, the site investigations consist mainly of a set of geoscientific factors.

The site investigation plan is used in the implementing organisation to extract separate site investigation programmes or work packages that are then contracted out to be executed. An example is drilling and mapping of a borehole or collecting and analysing existing geotechnical reports from near-by area, and so forth.

The following generic geoscientific datasets usually provide adequate information in the first phases of the siting process.

- Geological factors
- Geomechanical and seismic factors
- Hydrogeochemical factors, and
- Hydrogeological factors.

The detailed site characterisation activities are listed and described in detail in the site characterisation plan, which is usually part of the siting process documents. The typical activities include for example surface mapping, geophysical logging (airborne, surface, borehole), and borehole investigations.

5 FACILITIES ABOVE GROUND

5.1 Facility site

The location of the surface buildings and structures are illustrated for three cases (Figure 5-1, Figure 5-2 and Figure 5-3) according to experiences from other disposal facilities.

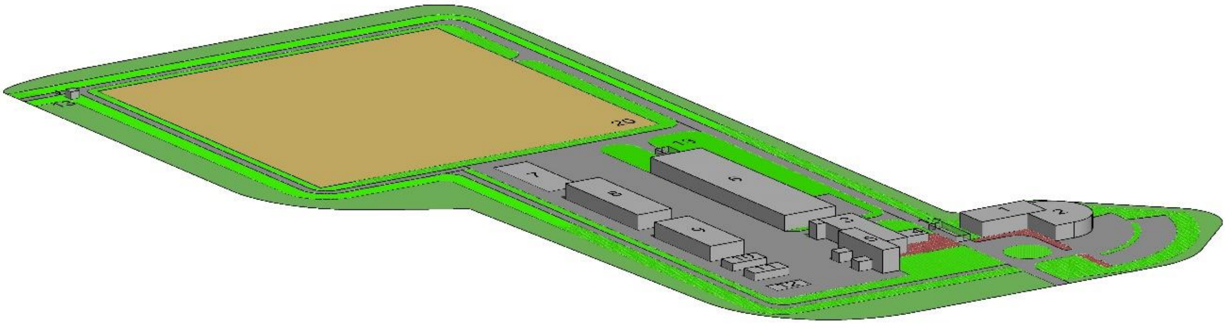

Figure 5-1. Above-ground arrangements of the National Facility and a 14 hectares footprint for the case where HLW is disposed in a DGR. The same arrangements would be needed solely for the intermediate depth repository even without the DGR. Figure AINS.

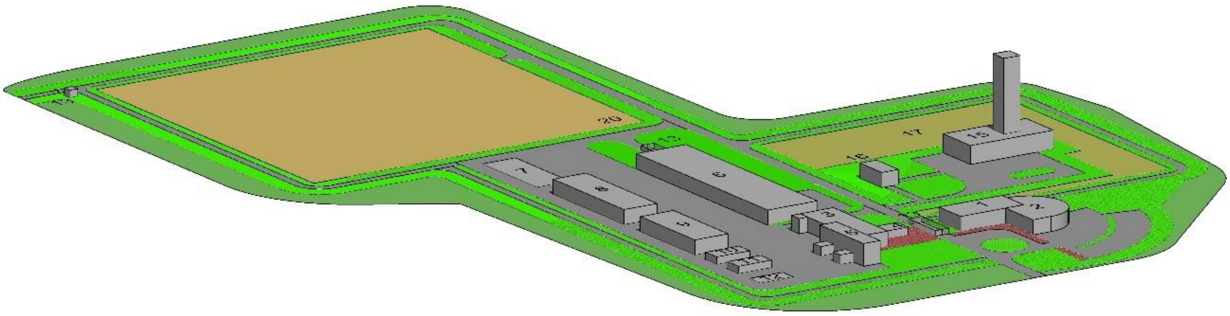

Figure 5-2. Above-ground arrangements of the National Facility and an 18 hectares footprint for the case where HLW is disposed in a deep borehole. Figure AINS.

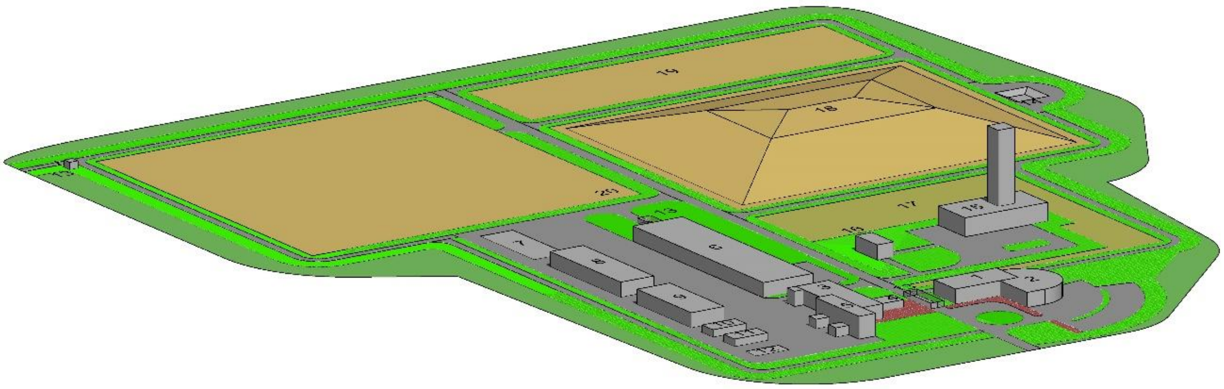

Figure 5-3. Above-ground arrangements of the National Facility and a 25 hectares footprint for the case where HLW is disposed in a deep borehole and an option for a landfill repository for non-radioactive decommissioning waste is used. Figure AINS.

The presented surface layouts are exemplary, and slight conservatism has been followed in production of the descriptions for the areas and volumes for all concepts and parts. The exemplary layouts are adaptable to more strict boundary conditions, and they can be varied and fitted to e.g. a narrow valley/property. In all previous three cases and Figures 5-1, 5-2 and 5-3, the surface arrangements related to the intermediate depth repository are considered.

The buildings are inside the facility fence, except the office building and the visitor centre. New roads will be built inside the facility fence. Figure 5-4 illustrates the four groups of buildings and areas of the National Facility property. The excavated material from disposal facility excavation and construction work is transported out of the facility.

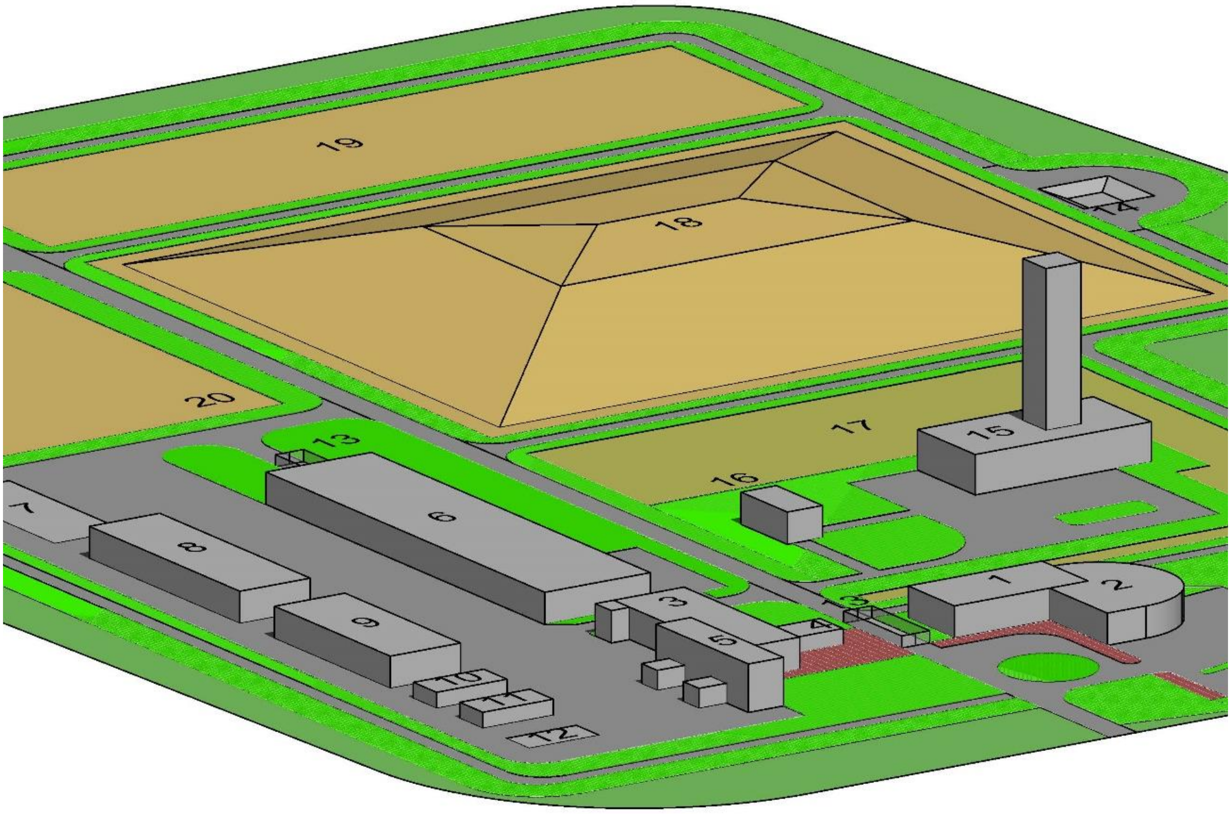

Figure 5-4. Four groups of buildings and surface areas of the National Facility. The first group on the background is formed by the landfill repository hill option (18) and related container laydown (19) and storage/construction area options (20). The second group includes the deep borehole area (15-17), and the third group includes the office building (1) and visitor centre (2) outside the facility fence. The fourth group is formed by the rest of the buildings related to the intermediate depth repository (and DGR) access routes and a shared storage/construction area, waste reception building, packaging, maintenance, research, security etc. Detailed index numbers and buildings are presented in Figure 5-5. Figure AINS.

5.2 Principles of facility layout

The existing infrastructure outside the disposal facility is to be utilised as far as possible. Examples of this include the road network, water and sewage lines, district heating and power supply.

Surveillance and monitoring functions are combined and centralized in the operation building and backup for these functions are located in tunnel portal building.

Provisions are made for stakeholder visitors to the security controlled area. The largest individual group of stakeholder visitors is two vans equal to 2 x 9 persons including the guides. The visitor centre is for all visitors and can receive much larger groups.

5.3 Supply of electricity to the disposal facility

The power supply for the disposal facility is arranged via two 20 kV connections. The surface facilities of the ventilation building and the tunnel portal building will have 20 kV transformers and substations. The personnel lift and other consumers in the repositories will have their own dry-type transformers. At the facility site, electricity will be supplied to the substations using underground cables.

5.4 Heating, water supply and drainage/sewage system

The underground facilities are heated by heating the inlet air with the district heating system. The district heating pipes will be installed beside the roads in a ditch connecting the above-ground buildings of the disposal facility.

Potable water will come from outside the National Facility. Domestic waste waters are led to the sewage network outside the facility fence. The sanitary waste waters from the underground are transported on a tank lorry for cleaning processing.

The seepage waters from the disposal facility are sedimented and any oil contained is separated near the lowest underground location at the -100 and -400 metres levels. After that, the seepage waters are pumped through the access tunnel (from the intermediate depth repository level via personnel shaft) to ground level and led to the nearby water system in a ditch. The waters from the basic drainage system of buildings and rainwater drainage system are also pumped and led to the nearby water system.

5.5 Traffic arrangements

Heavy goods traffic includes the transports of spent nuclear fuel canisters, LILW packages, bentonite and backfill products, diesel fuel, heavy machinery and building materials. Heavy goods traffic at the facility site consists of transports of excavated materials out of the facility in the construction phase and the transports of backfill materials to the disposal facility. Light goods traffic includes the transport of individual items and various accessories to the facility and removal of waste from the facility. The personnel traffic of the disposal traffic above ground is mainly based on the use of passenger cars. There are parking facilities outside the facility fence.

5.6 Personnel

During operational phase, most of the personnel at the disposal facility work mostly in single shifts. The security guards work in three shifts. At night, surveillance of the operation building takes place from the security guard centre. The support point of personnel handling nuclear fuel is in the operation building where the access control point for the controlled underground area is located. Other controlled areas are operation building, ventilation building, packaging plant, waste reception building, tunnel portal building and deep borehole area.

5.7 National Facility site buildings and structures

Figure 5-5 shows the buildings and areas at the disposal site.

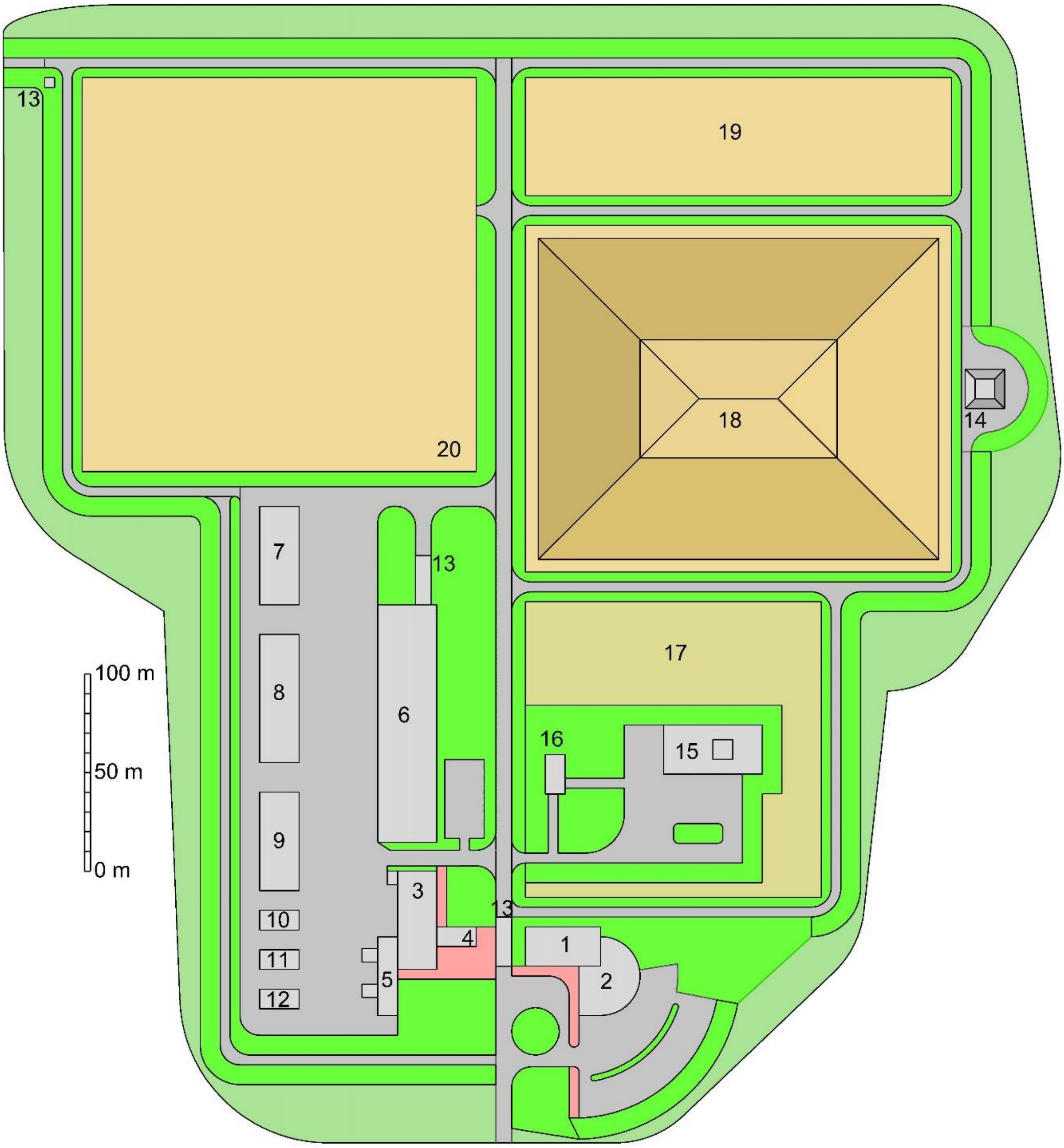

Figure 5-5. Buildings at the disposal site: 1) Office building 2) Visitor centre, 3) Operation building, 4) Guard, 5) Ventilation building, 6) Tunnel portal building, 7) Packaging plant area, 8) Waste reception building, 9) Maintenance and storage hall, 10) Research building, 11) Backup power supply, 12) Refuelling station, 13) Control, 14) Sedimentation pool option, 15) Emplacement building, 16) Base, 17) Deep borehole area, 18) Landfill repository option, 19) Container laydown area option, 20) Storage/construction area. Figure AINS.

Waste reception building

Waste reception building (index 8 in Figure 5-4 and Figure 5-5) is first for HLW, then for ILW and finally for VLLW and LLW reception control, contamination test, transfer from road transportation equipment to canister/waste transfer vehicle and temporary storage.

In this building, *canister transport casks* are stored with canisters while waiting for transfer to the DGR or deep borehole and empty canister transport casks pending return transfer. The number of positions for canister transport cask amounts to 14 KBS-3 type positions equal to one deposition tunnel need, and the building footprint is roughly 20 metres x 65 metres. Furthermore, there is a parking place for transport and access tunnel vehicles. The building is a controlled area. The location of the waste reception building meets the logistical need for proximity to other functions and flows. According to e.g. Finnish Radiation and Nuclear Safety Authority, an analogous building (encapsulation plant) with an analogous number of canisters does not need to withstand a heavy airplane crash because of limited number of spent fuel canisters – it is dimensioned for a light airplane crash.

Deep borehole area

The requirement for the size of the deep borehole area (index 17 in Figure 5-4 and Figure 5-5) comes from the drill rig height, which dictates the horizontal safety zone around it. The drill rig is about 50 metres tall, requiring a circular area with a radius of 50 metres. Therefore, for the purpose of this concept description, the area required for the borehole disposal is slightly conservatively assumed to be approximately 150 metres by 150 metres. The area consists of two main buildings: the Emplacement Building (including the enclosed disposal rig) and the Base Building (site office and support).

Operation building

Monitoring operations of the disposal facility are concentrated in the operation building (index 3 in Figure 5-4 and Figure 5-5), which also has social rooms for the staff of the disposal facility. The building is a controlled area.

The personnel shaft will be connected to the operation building and through it, and, in addition to personnel traffic, electricity will also be fed and seepage water removed from the intermediate depth repository level.

The disposal facility will rely on the services provided by the fire and rescue operations of the local municipality. The facility will not have its own fire station. The security guards at the disposal facility will be trained for manual fire-fighting duties.

Security patrols and surveillance of the disposal facility are centralised in the operation building. This control post is manned at all times, so it is the logical point for controlling access.

Ventilation building

The underground areas of the disposal facility are ventilated through a ventilation building (index 5 in Figure 5-4 and Figure 5-5). The building is a controlled area. (Only the uppermost part of the access tunnel has exhaust air function through the tunnel portal building.)

Backup power supply

There is a relatively small unit for backup power supply (index 11 in Figure 5-4 and Figure 5-5) on the area.

Research building

The monitoring samples are studied and temporarily stored in this building (index 10 in Figure 5-4 and Figure 5-5). There is also a small water chemistry laboratory in the building for monitoring purposes.

Tunnel portal building

The tunnel portal building (index 6 in Figure 5-4 and Figure 5-5) has a transformer station and a 20 kV substation for the power supply cable to be installed along the access tunnel. The tunnel portal building also has a variety of access control and communication technologies-related facilities, and it is located around the access tunnel portal. This building hosts also a pumping station for fire water and equipment for blending marker for underground water supply. It also takes care of the heat recovery of outlet air from the uppermost part of access tunnel.

Maintenance and storage hall

The equipment used for backfilling and closure of the underground repositories will be taken underground via the access tunnel. Also, waste will be transferred to the underground repositories via the access tunnel. A maintenance and storage hall (index 9 in Figure 5-4 and Figure 5-5) will be built for maintaining and repairing disposal and backfill equipment and vehicles. The hall also has the necessary storage facilities and vehicle washing equipment.

Visitor centre

The visitor centre (index 2 in Figure 5-4 and Figure 5-5) operates as the National Facility's public information centre, as well as a reception for visitors. The visitor centre has an exhibition, a sufficient number of meeting/seminar rooms, an auditorium and a cafeteria. The visitor centre is located outside the facility fence next to the office building.

Landfill repository

The landfill repository option includes a sedimentation pool (index 14 in Figure 5-4 and Figure 5-5), a container laydown area (index 19 in Figures 5-4 and 5-5) and a stack of waste and different layers (index 18 in Figures 5-4 and 5-5) described in more detail in Chapter 9. Figure 5-3, Figure 5-4 and Figure 5-5 illustrate the landfill option for non-radioactive waste.

Packaging plant

A packaging plant (index 7 in Figure 5-4 and Figure 5-5) for VLLW, LLW and ILW from medicine, research, industry etc. is needed for the accumulation of Norwegian waste during the 100 operation years of the National Facility. The footprint area of the packaging plant is 20 x 50 metres. The packaging plant is out of the scope of this assignment, but an area for this building is reserved.

Office building

The office building (index 1 in Figure 5-4 and Figure 5-5) is scaled for the size of NND, resulting in 70 office workers, based on the size of the Finnish nuclear waste management organisation. There are office rooms on two floors.

Refuelling station and oil tanks

There is a refuelling station (index 12 in Figure 5-4 and Figure 5-5) near the maintenance and storage hall. It is mainly for the vehicles dedicated for the disposal facility. Outsourced vehicle services do not normally use this refuelling station.

Storage area

A space for a cold storage hall and uncovered storage area (index 20 in Figure 5-4 and Figure 5-5) has been reserved for building materials for underground and above ground facility construction stage. There will not be much need for building materials during the operating phase. In the landfill disposal option, this same area is used for raw material handling and as a storage area.

Storage space reservation for containers

There is also a reservation for an area for containers (index 19 in Figure 5-4 and Figure 5-5) to be laid down before emplacement to the landfill repository.

6 INTERMEDIATE DEPTH REPOSITORY

6.1 Implementation

6.1.1 Underground facility

The facilities on the intermediate depth repository level and above (Figure 6-1) form openings that are needed for VLLW, LLW and ILW disposal. They include VLLW, LLW and ILW repository halls, access tunnel, inlet and exhaust air shafts and auxiliary rooms including control and maintenance rooms (which forms an over pressurized safety centre for the case of fire or cave in), electrical rooms, vehicle parking hall, sedimentation pool and pumping station for water seeping into the tunnel system. Openings other than the actual intermediate depth repository (i.e. VLLW, LLW and ILW halls) are also discussed in this chapter.

Before the disposal operations are started all above-mentioned openings will be built. Figure 6-1 presents the layout example for the facility for all Norwegian radioactive waste excluding high level waste. It is designed for a generic site without knowledge of local crystalline bedrock. The waste halls are tailored for NND based on experience and dimensions of the existing disposal facility in Loviisa, Finland (see also Figure 6-6 and Figure 6-7). The span for VLLW and LLW halls has been minimized in this example.

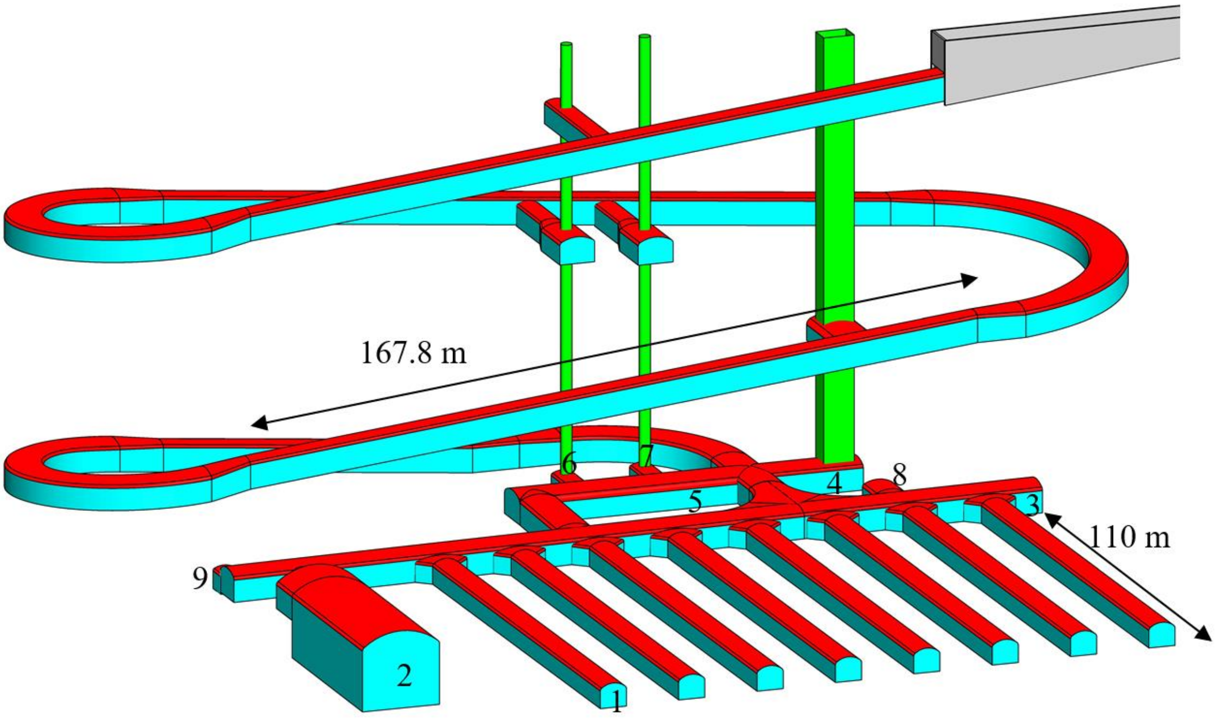

Figure 6-1. There will be eight VLLW/LLW halls (1) and one ILW hall (2) along the access tunnel and its side tunnel (3). Control and maintenance rooms (4) are located at the personnel shaft connection and parking hall (5) at the front of the inlet air shaft connection (6) and exhaust air shaft connection (7). There are also electrical rooms (8) and a sedimentation pool with a pumping station (9) at this intermediate depth repository level. The length of the straight basic access tunnel section is roughly 170 metres and VLLW/LLW hall 110 metres. Figure AINS.

Tunnel in front of the waste halls

There will be eight VLLW/LLW halls and one ILW hall along the access tunnel and its side tunnel. This tunnel area at the depth of 100 metres is almost horizontal and, together with the parking hall, it is dimensioned for the waste package and backfill transfer vehicles and other vehicles maneuvering. The width of this tunnel will be 8.5 m, and the vehicle clearance height is 4.5 m.

VLLW and LLW halls

VLLW and LLW are packed in 200 l drums and emplaced with a remote-controlled counterbalanced forklift to waste halls excavated for them (dimensions are presented in Figure 6-2). The span of the halls in this exemplary description is minimized because of less ground support need, and wider halls could also be used. The centre-to-centre distance between the halls is 18 m and the length of halls is 110 metres from the access tunnel wall line. The tunnel length for waste is 105 metres and the remaining 5 metres is for turning and plug reservation. With this length there are no remarkable challenges related to excavation technology, occupational safety or additional ventilation fans. For each hall there will be roughly 6400 barrel positions. The estimated total quantity of Norwegian VLLW and LLW (51,000 barrels) will be disposed of in eight halls.

ILW hall

ILW is packed in concrete containers and emplaced in a concrete basin in the ILW hall (Figure 6-2). The concrete basin provides mechanical support and radiation protection during the operational phase. The volume of the concrete basin is roughly 5500 m^3 and the length of hall is 63 metres from the access tunnel wall line. Above the concrete basin a bridge crane for roughly 10 tons capacity will be installed to emplace waste containers. The estimated total quantity of Norwegian ILW can be disposed of in one single hall.

6.1.2 Systems

Heating system

The purpose of the heating system is to maintain specified temperatures at the underground disposal facility (Saanio et al. 2013). Facilities where people work on a constant basis have more strict requirements for temperature.

The disposal facility is heated by heating the inlet air. Thermal energy is recovered from the exhaust air. The heating energy comes from local supplier via a district heating system, or from the electrically heated backup boiler.

The inlet air is heated at ground level in the ventilation building and distributed to the underground areas through the inlet air shaft. The exhaust air from the underground disposal facility is led via exhaust air shaft back to the ventilation building for heat recovery.

Ventilation system

Excavation causes dust emissions and the blasting explosion gases must be removed by temporary ventilation during construction stage. The purpose of the permanent ventilation system is to maintain sufficiently good air quality in the underground disposal facility. Radon and exhaust gas emissions from diesel-powered vehicles are typically the main factors deteriorating the air quality (Saanio et al. 2013).

The tunnel sections in front of waste halls on intermediate depth level have trunk channels for inlet and exhaust air, and these are connected to the inlet and exhaust air channels coming from the inlet air shaft and the exhaust air shaft. The access tunnel will be ventilated through the inlet air shaft and the exhaust air shaft according to fire compartmentalization. The inner diameter for both ventilation shafts is 2.5 m without rock support. The personnel shaft is pressurised with inlet air from above ground. The principle of ventilation is presented in Figure 6-3.

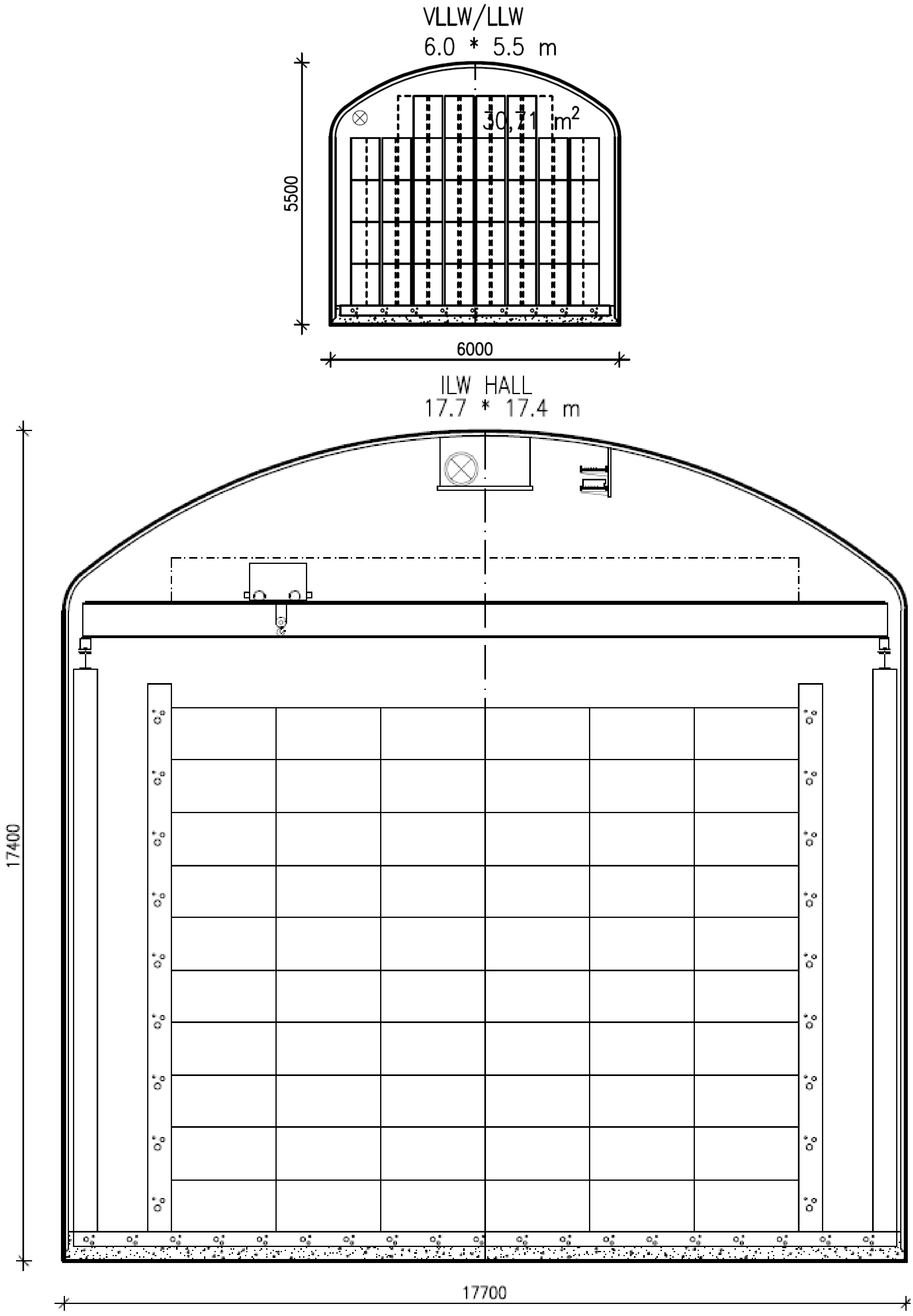

Figure 6-2. VLLW/LLW hall (upper) and ILW hall (lower) cross sections. Figure AINS.

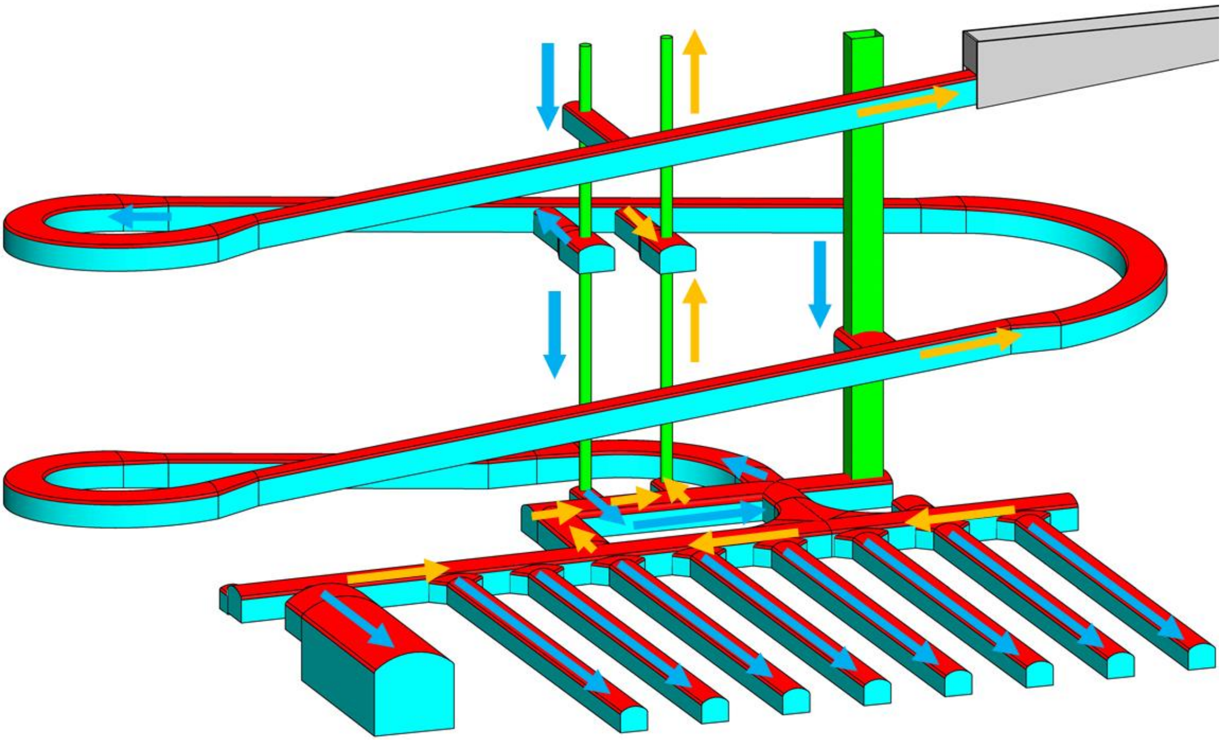

Figure 6-3. The principle of ventilation at the intermediate depth repository level. Blue arrows indicate inlet air and orange arrows exhaust air main flow directions. Figure AINS.

The exhaust air channels are used for extraction of smoke in case of fire. The ventilation channels will be fitted with fire insulation and safety locks will be installed in places where the channels cross from one fire compartment to another. Separate fans will be required for smoke extraction. Their capacity will be chosen on the basis of the worst case scenario regarding a fire in the disposal facility. In the VLLW/LLW/ILW halls, the inlet air channels are extended to the back ends of tunnels or halls while the exhaust air channels end at the hall entrances.

Water systems

During the construction phase, water is required for excavation and washing. During the operational phase, water is required for sanitary installations, maintenance washing and, if needed, for fire fighting.

Potable water is supplied to the intermediate depth repository level via the personnel shaft. Toilet sewage waters are collected in tanks at level -100 metres from where they are taken away by a sewage suction truck. Another alternative is to use dry toilets.

A tank for emergency fire hydrant water (and in construction stage for drilling) will be located at ground level, together with another tank for sprinkler water. The facilities with significant fire loads will be equipped with a sprinkler system. To create a circular pipeline, water will be fed from two different routes: the fire-fighting water pipe will be installed via both access tunnel and inlet air or personnel shaft.

Seepage water system

The purpose of the seepage water system is to collect the waters seeping from the bedrock and the maintenance washing waters to a sedimentation pool, allow them to settle and then pump the water from the sedimentation pool to ground level for removal (Saanio et al. 2013). The seepage water sedimentation pool is located at the -100 metre level and, from there, seepage waters will be pumped up in one stage during the intermediate depth repository operation.

Electrical systems

Electricity is supplied to the repository level through two 20 kV supply lines, one running through the inlet air or personnel shaft and the other through the access tunnel. There will be substations located at different locations underground.

The purpose of the lighting system is to provide suitable general lighting for the disposal facility, plus sufficiently efficient local lighting for places of work. The facilities will have a battery-backed emergency lighting system.

The purpose of telecom systems is to allow communications between members of personnel working in the underground and above ground disposal facility such as (Saanio et al. 2013):

- Internal telephone cable network
- Antenna systems
- Audio system (for emergency announcements)
- Computer network
- Signalling system (for sirens and flashing lights)
- The wireless telephone system
- Surveillance, security and safety systems (fire alarm, CCTV surveillance, access control, person positioning, signal light, emergency lighting and smoke extraction).

Disposal facility monitoring and control systems

The purpose of condition monitoring is to monitor the condition of the disposal facility and systems during the operating phase. Instrumentation systems are used for gathering and processing information on the condition of the facility and ensuring that working safety is good in the facility. The monitoring and control data are collected in the control room in the operational building. The following (Saanio et al. 2013) measurements can be carried out in the disposal facility:

- air, bedrock and water temperature measurements
- air humidity measurements
- drainage water level measurements
- air activity measurements
- CO-, CO2-, NOx- and radon content measurements
- air dust content measurements
- smoke detection
- (measurements related to nuclear material safeguards in not needed for VLLW and LILW).

Transfer systems

The personnel lift is connected to the operation building. The lift is used for the personnel traffic to the intermediate depth repository level (-100 metres).

The transfer and installation vehicles are used for transferring and installing waste packages and backfill materials.

The specific waste package transfer vehicle for the transfer of ILW waste packages from waste reception building via access tunnel to the ILW hall is illustrated in Figure 6-4. The VLLW/LLW package transfers can be done with the same vehicle or with a specific tractor platform. A bridge crane installed in the ILW hall is used for transferring the ILW packages to their positions in the waste hall. VLLW/LLW packages are emplaced in the waste halls with a remote-controlled counterbalanced forklift.

Figure 6-4. An example of the ILW package transfer vehicle and a bridge crane for emplacing packages in the ILW repository (TVO 2011).

The backfill materials are transferred underground from the ground level via the access tunnel.

6.1.3 Safety classification

The systems, structures and components important to safety shall be designed, manufactured, installed and operated so that their quality level and the inspections and tests required to verify their quality level are adequate considering any item's safety significance. To comply with this principle, the systems, structures and components of a nuclear facility are grouped into safety classes. The safety class provides the basis for defining the quality assurance requirements for the systems, structures and components of a nuclear facility. Safety classification forms the basis for determining the scope of regulatory controls by the Radiation and Nuclear Safety Authority (Saanio et al. 2013). In this report no suggestion for detailed safety classes is provided.

6.1.4 Fire safety

The layout for the disposal facility has been made in compliance with typical building codes and regulations. Later it needs to be further studied in relation to Norwegian regulations concerning e.g. the number of escape routes, escape distances and size of fire compartments.

The electrical substations are located in individual fire compartments. The electrical motors powering the lift are located at ground level so that they will not increase the fire load in the disposal facility.

Facilities with significant fire loads as well as exit routes will be separated into individual fire compartments. These facilities include electrical substations and stairways and other personnel access routes. The size of fire compartments is kept reasonable to avoid too long escape routes.

The exhaust air channels are used for extraction of smoke in case of fire. The fans and dampers of the smoke extraction system are controlled by smoke extraction stations installed by the fire squad entry route next to the control panel for the fire alarm system in two separate location above ground.

The intermediate depth repository level control and maintenance rooms next to the bottom of the personnel shaft form the safety centre. The safety centre and personnel and inlet air shafts are constantly pressurized to prevent smoke entering there. There are stairs and personnel lift in the personnel shaft and maintenance cage in both inlet and exhaust air shafts. The duplicated blowers are situated above ground in the operating building and ventilation building.

The facilities will be protected by an automatic fire alarm system. Smoke and temperature detectors and optical fibre cabling and sensors may be used. The disposal facility will be equipped with an express fire hydrant. The facilities with significant fire loads will be equipped with an automatic sprinkler system.

6.1.5 Facility adaptation for different waste volumes

In this report, the layout of the disposal facility is demonstrative and based on an imaginary site without knowledge about the local characteristics of the crystalline bedrock. The VLLW, LLW and ILW estimations used for now as a basis for the design may also change and thus affect the required volume and layout of the repository openings.

For extending the intermediate depth repository, there is a short niche in front of the current VLLW/LLW halls (Figure 6-5). By extending this tunnel there will be room to excavate more waste halls at the depth of 100 metres. The current length of waste halls and ILW concrete basin is also possible to extend until the beginning of individual waste hall excavation work.

6.1.6 Facility construction in phases

It is assumed that, because of very limited amount of waste and easy separation of the construction and operating stages, all underground openings will be excavated in one phase (assuming that no DGR is built). If wanted, the last waste hall can be furnished later in parallel with the operation of the repository.

6.1.7 Underground facility production

The requirements of the disposal facility affect the materials that are to be used. Only licensed materials are allowed to be taken into the underground disposal facility, and for this reason the designer must be aware, for example, of which part of the disposal facility a planned grouting operation is needed, because the material requirements are different for different openings. The requirements are stricter in close proximity to the waste halls (Saanio et al. 2013).

The underground openings production method for ventilation shafts is raise boring. For tunnels and possibly also for the personnel shaft, the production method is drilling and blasting. Traditional rock support methods will be used according to the lifecycle of each underground opening.

Openings produced by drilling and blasting

The first stage in excavating any tunnel is drilling of pilot holes. The bedrock is examined from these holes, so the grouting, excavation and supporting plans can be adapted to match the bedrock conditions. For the waste halls, the pilot hole investigations have a more significant role than with the other tunnels because, according to these investigations, the decision, if needed, will be made to shorten the waste hall from the original design length in the layout if the bedrock characteristics are not favourable for disposal. The reason can be, for example, a hydraulically conductive structure that intersects the waste hall, which then cannot be used for disposal. Nor can disposal be made at the proximity of the structure, and, if the structure continues along the hall for a long section, it may be sensible to stop the excavation.

The excavation of tunnels is done with a similar cycle everywhere in the disposal facility. After possible pre-grouting, the tunnel section is drilled, drillholes charged and blasted, the blasting fumes are ventilated out, rock transported away and the produced section is measured.

After the tunnels/halls are excavated, their surfaces are mapped and, in the waste halls, different measurements are also conducted to discover the suitability for disposal (Saanio et al. 2013).

The personnel shaft preliminary cross section is 5.2 x 7 m without rock support. Basic dimensions of the waste halls are presented in Figure 6-2.

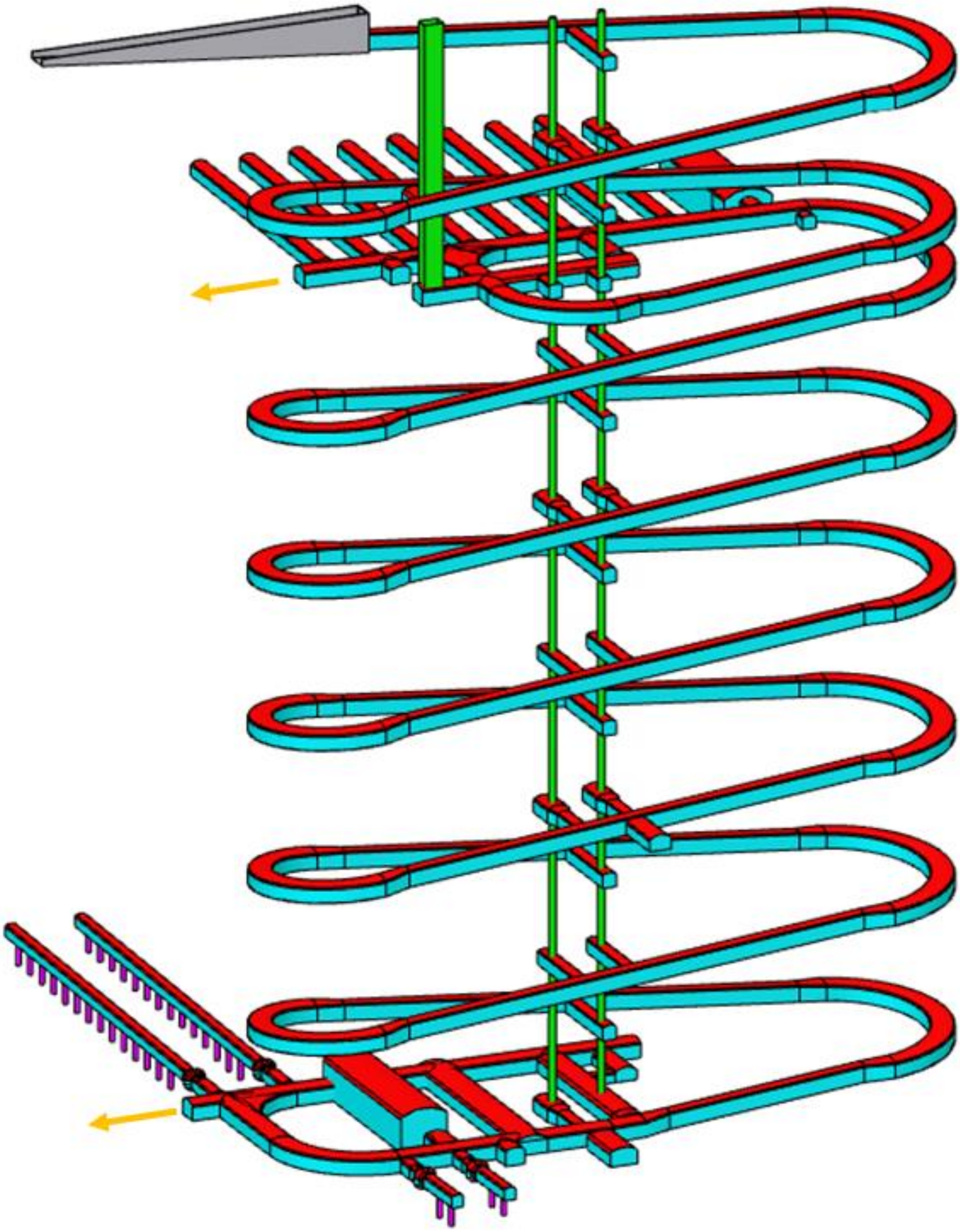

Figure 6-5. Layout example for the underground disposal facility. The waste halls form the intermediate depth repository (in the upper part of the figure). The deposition tunnels and deposition holes form the DGR (in the lower part of the figure). The arrows show the potential expansion direction if more repository room would be needed for VLLW, LLW, ILW and/or HLW. Figure AINS.

Openings produced by raise boring

After pre-grouting, the ventilation shafts are implemented first by drilling a pilot hole through the selected shaft section that is to be opened. After the pilot hole has been evaluated to be suitable, the drill bit for widening is installed on the device at the bottom, and then the shaft is widened to a desired 2.5 metre diameter. Widening can first be made with a smaller diameter bit and again with a larger one. The inner diameter for both ventilation shafts is 2.5 m without rock support.

6.1.8 Demonstrations

For the intermediate depth repository, no separate demonstration waste halls are assumed to be needed.

6.2 Operation

Different types of waste are disposed of in campaigns of suitable duration. Due to technical aspects concerning backfilling, it appears preferable to implement the disposal activity campaigns on the basis of waste type. The total amount of seepage water flow is also limited by closing openings as soon as possible after the waste packages have been placed.

If a DGR is not needed, in 100 metre depth the disposal of existing ILW will be done in the first disposal campaign. The second disposal campaign will be the already existing VLLW and LLW disposal to the shared VLLW and LLW openings and closure of these same rooms at the depth of 100 metres. One option is to use non-radioactive decommissioned and crushed concrete as one backfill component in the VLLW and LLW or other underground openings.

The third campaign will be the disposal of VLLW/LLW and ILW accumulating between 2050 to 2150 to the last two VLLW/LLW openings and ILW concrete basin. This will be followed by decommissioning of the packaging plant and other necessary decommissioning works and closure and plugging for the rest of the underground openings will be done. Then the remaining buildings and the site above ground can be put to some other use or dismantled.

6.2.1 Activities and schedule

The emplacement of ILW takes roughly one year. The emplacement of VLLW and LLW and backfilling the first six waste halls with plug production takes roughly two years. The remaining two waste halls will be filled with waste accumulating in Norway until year 2140.

6.2.2 Transfer and installation of waste packages

Intermediate-level waste is transported to the ILW hall (Figure 6-6) in a specially designed vehicle (Figure 6-4). The VLLW/LLW package transfers can be done with the same vehicle or with a tractor platform. The vehicle and the load are checked in waste reception building before they are taken underground via access tunnel. The unloading is carried out by remote-controlled crane (Figure 6-4). VLLW/LLW packages are emplaced to the waste halls (Figure 6-7) with a remote-controlled counterbalanced forklift.

Figure 6-6. An example of an ILW waste hall and the concrete basin under construction. Picture: Ari Haimi (Nummi 2018).

Figure 6-7. An example of a VLLW/LLW hall. Picture: Ari Haimi (Fortum 2013).

6.2.3 Backfilling

This section briefly describes an example of the backfilling and plugging of the ILW and VLLW/LLW halls.

Backfilling with crushed rock is used in the ILW hall which contains engineered barriers that need to be protected from mechanical impacts and have a large span and is more susceptible to rock damage. The possible void between the ILW packages is filled with concrete. VLLW/LLW halls will probably be backfilled with crushed rock too, but it is not obligatory. Plugs of reinforced concrete are positioned at the entrances of the waste halls (Nummi 2018).

6.2.4 Controlled and uncontrolled areas and phases

The difference between a controlled and uncontrolled area or phase is an issue of being able to measure the radiation doses to which personnel are exposed.

Waste packages are uncontaminated when they are transferred and emplaced underground. VLLW, LLW and ILW waste halls in the intermediate depth repository are defined as controlled areas always when there is waste present, waste is emplaced there, or waste halls are under backfilling work. During waste transfer, the whole underground tunnel system is a controlled area – not only the waste halls themselves. The previous excavation and construction work as well as following plug construction work are done in the uncontrolled phase/area. The purpose of this division is to control the movements of personnel in an area where there is a possibility of direct radiation and to measure the radiation doses they receive. During the uncontrolled phase and working in uncontrolled area, access is still controlled but not because of reasons of radiation protection: radiation doses of people are not measured, except if radon requires it.

6.2.5 Radiation protection

The purpose of radiation monitoring is to measure and monitor the activity of disposal facility air and the radiation doses received by personnel. The major source of airborne radioactivity is assumed to be radon, which is filtered to the underground rock facilities. If the radon content of the air exceeds the permitted limit, ventilation is increased. Besides radon gas, the employees are exposed to radiation doses emanating from waste packages. The periodic services, maintenance and cleaning that take place in the disposal facility normally cause no radiation doses to personnel (Saanio et al. 2013).

6.2.6 Incidents and accidents

In addition to normal operating activities, provisions are also made for operational incidents and accident conditions in the design of the disposal facility.

An operational incident can be restored back to normal operation in a short period of time. When normal operation is restored, the facility personnel may receive radiation doses but no radioactivity escapes from the facility.

Accidents are caused by serious equipment failures, erroneous actions by people or by exceptional external events. In some situations, a flawed plan may cause an accident. Accident conditions may result in major releases of radioactivity. Significant amounts of radioactivity may also escape outside the facility. People outside the facility may receive radiation doses. After an accident, the operation of the facility will be suspended until the situation has been cleared, corrective actions have been taken and normal operation is again possible (Saanio et al. 2013).

The objective is to design the disposal facility so that incorrect operation will not result in an accident. This report does not cover any analysis for incidents and accidents.

6.2.7 Safeguards

Safeguards do not apply to the intermediate depth repository. The fundamentals of safeguards apply only to high level waste as described in Section 7.2.7. This report does not cover any detailed plan for safeguards.

6.2.8 Monitoring

It is important to start baseline studies and monitoring well before the construction activities on the site so that a sufficient baseline can be established. Monitoring shall be continued during the whole construction and operation phase of the disposal facility, until the time of closure.

The environmental impacts of the project shall be monitored as well as the function of the engineered barriers to ensure that they function as expected. It is also necessary to gather data and provide feedback for construction and design on the impact of construction on the geosphere and surface environment.

Monitoring needs to demonstrate that the conditions in the surroundings of the disposal facility remain favourable (resembling the conditions at the site before the disposal facility existed) for long-term safety despite facility construction, operation and closure. It shall also collect additional information regarding long-term safety critical properties of the site for developing site models and ensuring the suitability of the site.

The monitoring programme can be divided into:

- Engineered barriers
- Rock mechanics (e.g. bedrock movements, rock stress, seismics and excavation-related blasts i.e. safeguards)
- Hydrology and hydrogeology (e.g. groundwater level, flow and pressure)
- Hydrogeochemistry (groundwater chemistry)
- Surface environment (impact and conditions)

6.3 Decommissioning and closure

The closure phase extends from the intermediate depth repository level to the ground level and is done after all VLLW/LLW and ILW packages are emplaced and all waste halls are backfilled and plugged.

The requirements regarding closure differ from those set for backfilling and closure of the waste halls. One key purpose of engineered release barriers, such as the backfilling and closure structures, is to limit the migration of radioactive materials via excavated facilities. The backfill materials and closure structures must prevent the formation of significant flow routes between ground level and the waste halls. The backfill materials and closure structures must also support the surrounding bedrock and prevent the inadvertent entry of people into the facilities. In addition to this, the materials used for closure must not have a significant harmful impact on the performance of the multi-barrier system (Saanio et al. 2013).

6.3.1 Dismantling work

Closure begins with the dismantling of structures and systems so that harmful quantities of materials are not left in the facility. After that, the facility is backfilled and plugged using appropriate closure structures (Saanio et al. 2013).

6.3.2 Closure

The closure includes all backfill and closure structures, i.e., plugs, outside the waste halls and waste hall plugs. The closure of the disposal facility will complete the isolation of the radioactive waste from the biosphere and restore the favourable natural conditions in the bedrock. The closure of the tunnels and other underground openings will prevent the formation of preferential flow paths between the ground surface and waste halls (Posiva 2012b). In the long term, the function of the closure is to maintain the favourable conditions in the bedrock surrounding VLLW/LLW and ILW. The design for closure of the disposal facility is based on the geological and hydrogeological environment (main fracture zones and hydraulic conductivities of the bedrock). An example of a Finnish closure design is presented in Figure 6-8, and the same materials and type of ideology is assumed to be used for the National Facility.

Closure of investigation boreholes

Several deep boreholes for bedrock investigation purposes need to be done at the disposal facility site or in its vicinity, and many of them reach the disposal depth, its near-field or go considerably deeper. In addition, there will be shallower holes for groundwater and other investigations. Even though the boreholes will not be a part of the underground disposal facility, they are considered in its closure due to their proximity to it. In addition to the deep investigation holes made from the ground surface there will also be holes made from underground openings that will be closed.

The investigation holes will not penetrate the repository openings, but many of them will be at the same depth and connected to the disposal facility openings via natural fractures in the bedrock. The closure of the investigation boreholes should be done so that the flow routes they form between the disposal depth and the ground surface can be sealed. By doing this, the dilution of the groundwater at disposal depth caused by entering surface waters can be prevented and also the transportation of radionuclides to the biosphere by this route can be prevented in case a waste package failure would occur (Saanio et al. 2013).

The boreholes are preliminarily assumed to be backfilled following the principles in Saanio et al. (2013). Borehole sections are backfilled with bentonite clay installed in a perforated copper tube to the depth of 500 m. Below this depth, the sparsely fractured borehole sections will be backfilled with bentonite installed by transporting it down the hole to the desired depth in a container and then pushed out. The borehole sections with high hydraulic conductivities will be closed with concrete. At the upper section, a copper plug will be installed, and above it there will be concrete material.

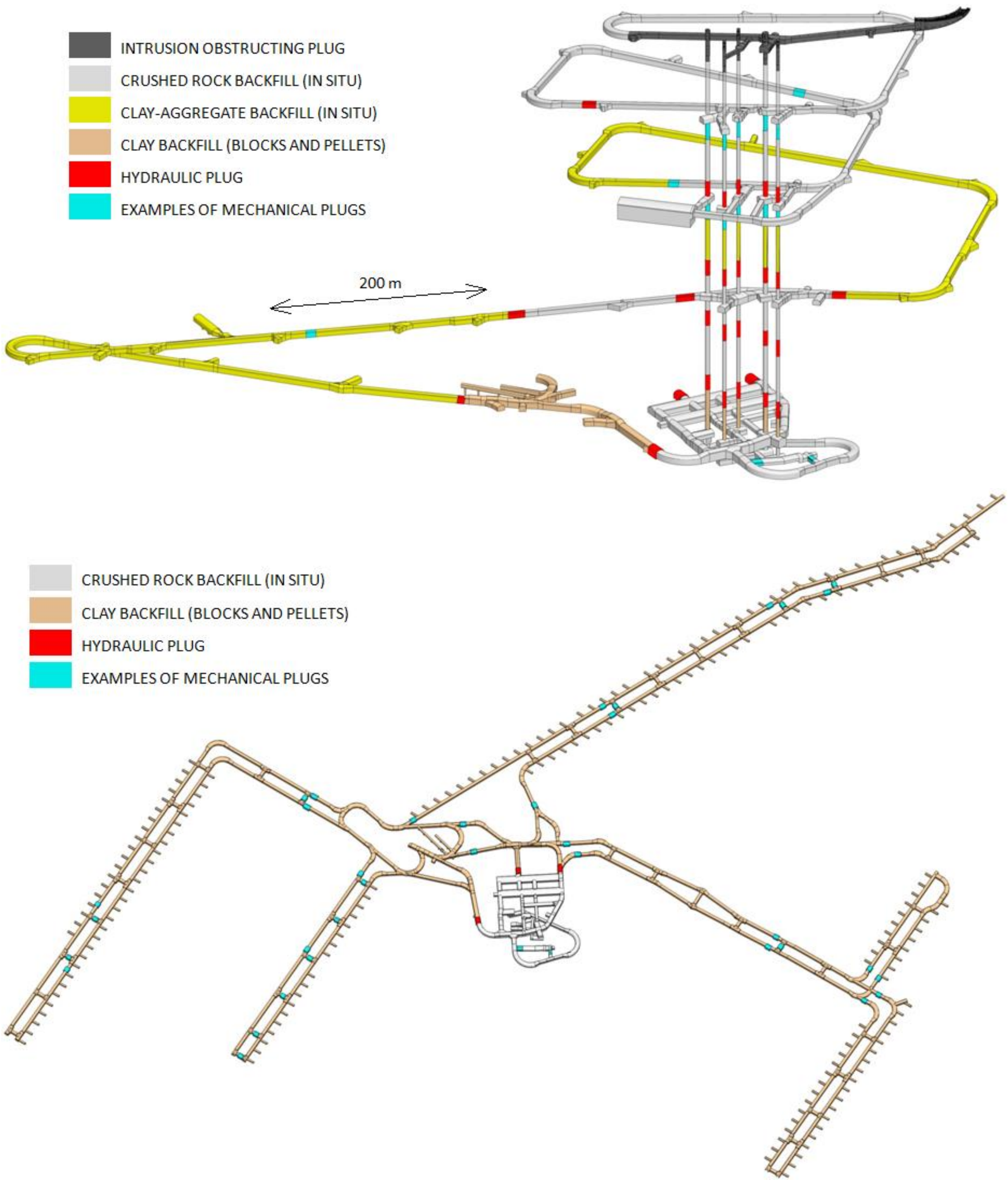

Figure 6-8. Reference design for the closure of the Finnish disposal facility, including a deep geological repository and a LILW repository. Figure AINS (Posiva 2012b).

6.3.3 Foreign materials remaining in the facility

It shall be controlled that no significant quantities of materials harmful to the performance of release barriers enter the repositories. The migration of materials detrimental to long-term safety of also HLW disposed in the same area shall be minimised. For this purpose, estimations about the quantities of foreign materials that remain in the disposal facility after it has been closed need to be done.

7 DEEP GEOLOGICAL REPOSITORY

7.1 Implementation

7.1.1 Underground facility

The DGR consists of the HLW repository, but other necessary openings are also discussed in this chapter. These include the access tunnel, inlet and exhaust air shafts, reloading hall, demonstration tunnels and auxiliary rooms including over pressurized safety centre, electrical rooms, vehicle parking hall, sedimentation pool and pumping station for water seeping into the tunnel system (Figure 7-1). Personnel shaft would be in use on the DGR (-400 m) level only one operational year (it is not needed for one or two-year cold testing). There is no rationale to use double or triple that time for building demanding structures in the very deep personnel shaft with uneven rock walls and water leakages (which is very challenging in terms of accessibility and occupational safety during furnishing work). It is assumed that the personnel shaft does not reach the -400 metres depth, but in can be added to the concept during more detailed design if wanted.

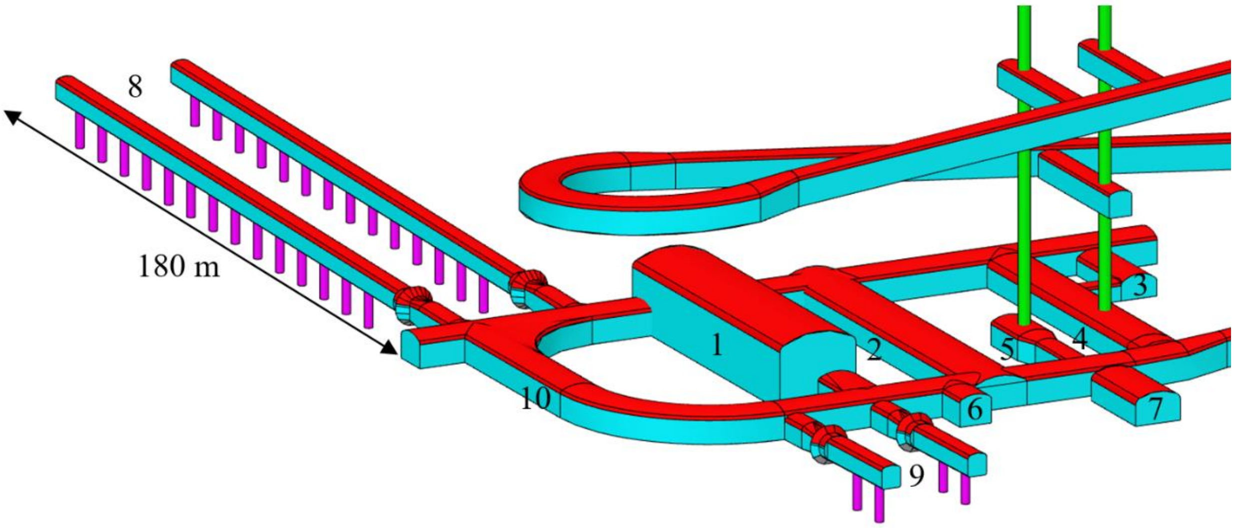

Figure 7-1. Auxiliary rooms include the reloading hall (1), parking hall (2), safety centre (3), inlet air (4) and exhaust air (5) shaft connections with ventilation equipment, electrical rooms (6), the sedimentation pool with the pumping station (7), all along the U-shaped transfer tunnel (10). Deposition tunnels (8) and demonstration tunnels (9) are also along the transfer tunnel. Figure AINS.

The underground disposal facility also includes an intermediate depth repository for VLLW, LLW and ILW, which is described in Chapter 6. The personnel shaft will reach the intermediate depth (-100 m level).

Before the disposal operations are started, the access routes, transfer tunnel, reloading hall, auxiliary rooms, demonstration tunnels and two deposition tunnels will be built. Figure 3-1 presents the layout example for the facility for all Norwegian radioactive waste. It is designed for a generic site without knowledge of local crystalline bedrock.

Reloading hall

The *reloading hall* is placed at the central area of DGR level, closest to the deposition tunnels and access tunnel, so that the canister can be transferred to the deposition holes with very little impact on the other parts of the auxiliary rooms (Figure 7-1). The dimensions of the reloading hall provide positions for 2 *canister transport casks* on the load carriers. The total capacity for canister storage in the waste reception building above ground corresponds to the quantity of canisters that could be deposited in one deposition tunnel.

In the reloading hall, the canisters are reloaded from the *access tunnel vehicle* to the *canister installation vehicle*. The primary connections to the hall are the access tunnel and the *transfer tunnel* to the repository (deposition tunnels and deposition holes).

The functional requirements governing the design of the hall include: to lay down a canister transport cask on the load carrier, a radiation-protected room for the transferring of canister from the canister transport cask to the canister installation machine, the unloading and installation of shock absorbers of canister transport cask, a bridge crane, nuclear material control, verification of the security and absence of transfer damage to the canister. The hall is designed so that the access tunnel vehicle always arrives at one end of the hall and the canister installation vehicle at the other end of the hall (Figure 7-2).

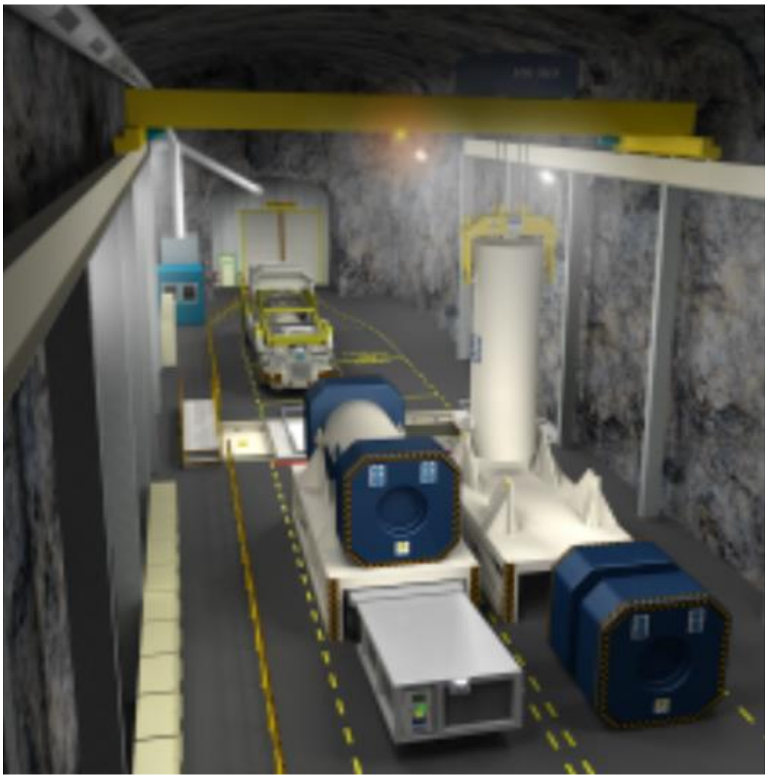

Figure 7-2. An example of a reloading hall, visualization of preliminary arrangements for SKB. The access tunnel vehicle is in front and the canister installation vehicle is on the background (Toze AB 2020).

Transfer tunnel

The U-shaped transfer tunnel is situated on DGR-level. Along this transfer tunnel are deposition tunnels, the reloading hall, demonstration tunnels and auxiliary rooms. The width of the transfer tunnel will be 8.5 m both in straight and in curved sections. The vehicle clearance height of the profile is the same as for the access tunnel, 4.5 m.

Deposition tunnels

Deposition tunnels will be excavated and deposition holes will be drilled in advance of the operational phase of DGR. The KBS-3 type disposal canisters are emplaced in holes drilled in the deposition tunnel floors. There will be eleven 7 m deep holes and seventeen 8.2 m deep holes. Hole diameter is 1.75 m for all deposition holes (Figure 7-3).

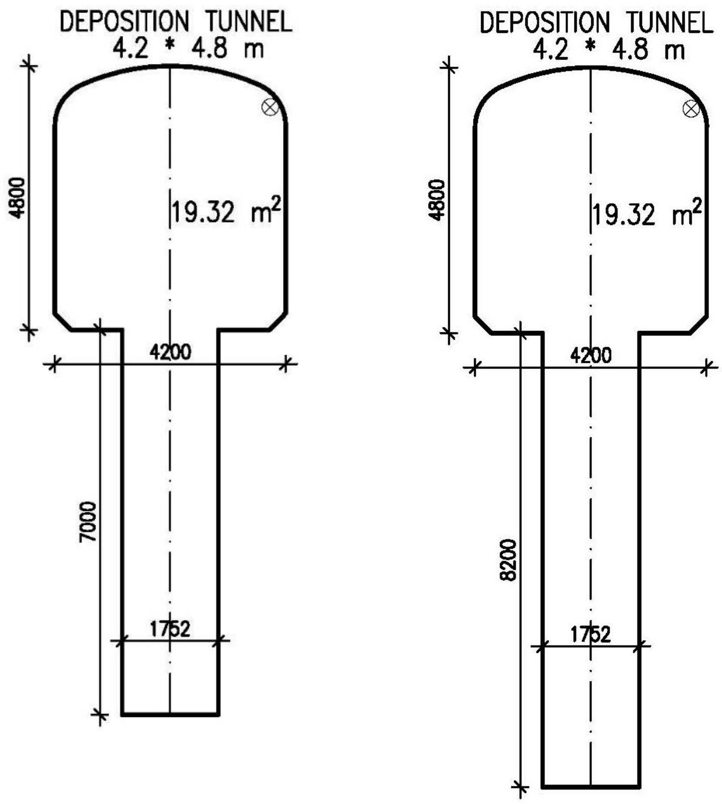

Figure 7-3. Cross-sectional view of a deposition tunnel. On the left cross-section from a deposition hole position for 3.55 m tall canister (11 pieces) and on the right for 4.75 m tall canister position (17 pieces). Figure AINS.

This report assumes the centre-to-centre distance between the canisters to be 10.0 m and the centre-to-centre distance between the deposition tunnels to be 25.7 m. This assumption is preliminary and will be updated after case-specific thermal dimensioning calculations are performed. It is assumed that 20 % of the deposition tunnel length needs to be rejected for deposition hole positions because of geological reasons. In practice, the distance between the canisters can be less than 8 m, but 2 m extra has been used. This is for potential fractures that prevent theoretical optimum distance to be used between the canisters.

The maximum length of deposition tunnels is 180 metres from the transfer tunnel wall line. With this length, there are no remarkable challenges related to excavation technology, occupational safety or additional ventilation fans. The estimated total quantity of Norwegian spent nuclear fuel will be disposed of in 28 disposal canisters. These can be disposed of in two of the deposition tunnels described above.

7.1.2 Systems

The systems of the DGR and the intermediate depth repository (Section 6.1.2) are mostly shared.

Heating system

The purpose of the heating system is to maintain specified temperatures at the underground disposal facility (Saanio et al. 2013).

The disposal facility is heated by heating the inlet air. Thermal energy is recovered from the exhaust air. The heating energy comes from local supplier via a district heating system, or from the electrically heated backup boiler.

The inlet air is heated at ground level in the ventilation building and distributed to the underground areas through the inlet air shaft. The exhaust air from the underground disposal facility is led via exhaust air shaft back to the ventilation building for heat recovery.

Ventilation system

Excavation causes dust emissions and the blasting explosion gases must be removed by temporary ventilation during construction stage. The purpose of the permanent ventilation system is to maintain sufficiently good air quality in the underground disposal facility. Radon and the exhaust gas emissions from diesel-powered vehicles are typically the main factors deteriorating the air quality (Saanio et al. 2013).

The transfer tunnel on the DGR level has trunk channels for inlet and exhaust air, and these are connected to the inlet and exhaust air channels coming from the inlet air shaft and the exhaust air shaft. The inner diameter for both ventilation shafts is 2.5 m without rock support. The access tunnel will be ventilated through the inlet air shaft and the exhaust air shaft according to fire compartmentalization. The principle of ventilation is presented in Figure 7-4.

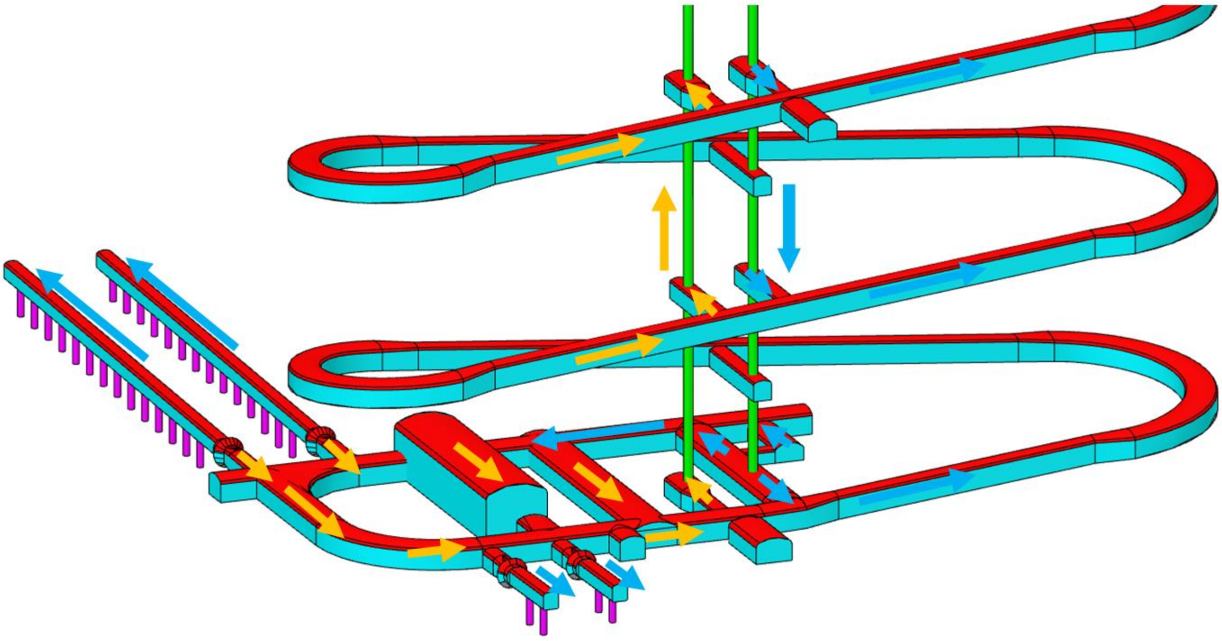

Figure 7-4. The principle of ventilation in the DGR. Blue arrows indicate inlet air and orange arrows exhaust air main flow directions. Figure AINS.

The exhaust air channels are used for extraction of smoke in case of fire. The ventilation channels will be fitted with fire insulation and safety locks will be installed in places where the channels cross from one fire compartment to another. Separate fans will be required for smoke extraction. Their capacity will be chosen on the basis of the worst case scenario regarding a fire in the disposal facility. In the deposition tunnels, the inlet air channels are extended to the back ends of tunnels while the exhaust air channels end at the tunnel entrances.

Water systems

During the construction phase, water is required for excavation, drilling deposition holes and washing. During the operational phase, water is required for sanitary installations, maintenance washing, cooling the concrete castings of plugs and if needed for the fire fighting (Saanio et al. 2013).

Potable water is delivered to the DGR in separate casks. Toilet sewage waters are collected in tanks at the level of -400 metres from where they are taken away by a sewage suction truck. Another alternative is to use dry toilets.

A tank for emergency fire hydrant water (and in the construction stage for drilling) will be located at ground level, together with another tank for sprinkler water. The facilities with significant fire loads will be equipped with a sprinkler system and another tank for DGR is located at the -300 metres level. The facilities with significant fire loads will be equipped with a sprinkler system. To create a circular pipeline, water will be fed from two different routes: the fire-fighting water pipe will be installed via both the access tunnel and the inlet air shaft.

Seepage water system

The purpose of the seepage water system is to collect the waters seeping from the bedrock and the maintenance washing waters to a sedimentation pool, allow them to settle and then pump the water from the sedimentation pool to ground level for removal. Line booster pump stations will be installed in the access tunnel niches approximately every 500 metres (Saanio et al. 2013). The seepage water sedimentation pool is located at the -400 metre level.

Electrical systems

Electricity is supplied to the repository level through two 20 kV supply lines, one running through the inlet air shaft and the other through the access tunnel. There will be substations located at different locations underground.

The purpose of the lighting system is to provide suitable general lighting for the disposal facility and sufficiently efficient local lighting for places of work. The facilities will have a battery-backed emergency lighting system.

The purpose of telecom systems is to allow communications between members of personnel working in the underground and above ground disposal facility such as (Saanio et al. 2013):

- Internal telephone cable network
- Antenna systems
- Audio system (for emergency announcements)
- Computer network
- Signalling system (for sirens and flashing lights)
- The wireless telephone system
- Surveillance, security and safety systems (fire alarm, CCTV surveillance, access control, person positioning, signal light, emergency lighting and smoke extraction).

Disposal facility monitoring and control systems

The purpose of condition monitoring is to monitor the condition of the disposal facility and systems during the operating phase. Instrumentation systems are used for gathering and processing information on the condition of the facility and ensuring that working safety is good in the facility. The monitoring and control data are collected in the control room in the operational building. The following (Saanio et al. 2013) measurements can be carried out in the disposal facility:

- air, bedrock and water temperature measurements
- air humidity measurements
- drainage water level measurements
- air activity measurements
- CO-, CO_2-, NO_x- and radon content measurements
- air dust content measurements
- smoke detection
- measurements related to nuclear material (high level waste) safeguards.

Transfer systems

The transfer and installation vehicles are used for transferring and installing fuel canisters, bentonite blocks and backfill materials.

The *access tunnel vehicle* (Figure 7-5) for the transfer of canister transport containers from the waste reception building via access tunnel to the reloading hall will consist of a platform truck in accordance with the same principle as SKB's current terminal vehicles. Short horizontal transfers of the canister transport cask will be done with a bridge crane in the reloading hall.

Figure 7-5. An example of an access tunnel vehicle for transferring fuel transport containers in the access tunnel (SKB 2015).

A disposal canister is moved with a vehicle (Figure 7-6) from the reloading hall to the deposition tunnel and installed in a deposition hole. During transfer, the canister is covered with a radiation shield. Its function is to protect the environment from the radiation of the spent fuel and the canister from outside disturbances (Saanio et al. 2013).

Figure 7-6. An example of a canister transfer and installation vehicle (Posiva 2016).

The bentonite blocks to be installed in the deposition holes are transferred from the temporary laydown area in the -400 metres level parking hall to the deposition tunnels for installation in the deposition holes using the bentonite buffer installation (Figure 7-7) and transfer devices.

Figure 7-7. An example of a bentonite buffer installation device (Posiva 2016).

The backfill materials are transferred to underground from ground level via the access tunnel.

7.1.3 Safety classification

The safety classification fundamentals of the DGR have been described together with the intermediate depth repository level in Section 6.1.3. In this report no suggestion for detailed safety classes is provided.

7.1.4 Fire safety

The layout for the disposal facility has been made in compliance with typical building code and regulations. Later it needs to be further studied in relation to local Norwegian regulations concerning, e.g., the number of escape routes, escape distances and size of fire compartments.

The electrical substations are located in individual fire compartments.

Facilities with significant fire loads as well as exit routes will be separated into individual fire compartments. These facilities include e.g. electrical substations and other personnel access routes. The size of fire compartments is kept reasonable to avoid too long escape routes.

The exhaust air channels are used for extraction of smoke in case of fire. The fans and dampers of the smoke extraction system are controlled by smoke extraction stations installed by the fire squad entry route next to the control panel for the fire alarm system in two separate location above ground.

The DGR level safety centre is located next to the bottom of the inlet air shaft. The safety centre and inlet air shaft are constantly pressurized via the inlet air shaft to prevent smoke entering there. There are maintenance cages in both inlet and exhaust air shafts. The duplicated blowers are situated above ground in the operating building and ventilation building.

The facilities will be protected by an automatic fire alarm system. Smoke and temperature detectors and optical fibre cabling and sensors may be used. The disposal facility will be equipped with an express fire hydrant. The facilities with significant fire loads will be equipped with an automatic sprinkler system.

7.1.5 Facility adaptation for different waste volumes

In this report the layout of the disposal facility is demonstrative and based on an imaginary site without knowledge about the local characteristics of the crystalline bedrock. The number of canisters for spent fuel disposal used as the basis for the design may also change and thus affect the required volume and layout of the repository openings.

For extending the transfer tunnel, there is already a short niche in front of the current deposition tunnels. By extending the transfer tunnel (Figure 6-5) there will be room to excavate more deposition tunnels. Current length of deposition tunnels is also possible to extend until the beginning of individual deposition tunnel excavation work.

7.1.6 Facility construction in phases

It is assumed that because of the very limited amount of waste and easy separation of the construction and operating stages, all openings will be constructed in two phases. The first phase is the construction and operation of underground demonstration openings and access routes to the DGR level. The second phase is the construction of the actual repository openings on both -100 and -400 levels and auxiliary rooms. The intermediate depth repository level openings and the DGR auxiliary rooms can be excavated parallel with the operation of demonstration tunnels if wanted.

7.1.7 Underground facility production

The requirements for the disposal facility affect the materials that are to be used. Only licensed materials are allowed to be taken into the underground disposal facility, and for this reason the designer must be aware of, for example, in which part of the disposal facility a planned grouting operation is needed, because the material requirements are different for different openings. The requirements are stricter in close proximity to the deposition holes (Saanio et al. 2013).

The underground openings production methods for the ventilation shafts is raise boring and for deposition holes it is full-face vertical push-reaming technique. For tunnels, the production method is drilling and blasting. Traditional rock support methods will be used according to the lifecycle of each underground opening.

Openings produced by drilling and blasting

The first stage in excavating any tunnel is drilling of pilot holes. The bedrock is examined from these holes, so the grouting, excavation and supporting plans can be adapted to match the bedrock conditions. For the deposition tunnels, the pilot hole investigations have a more significant role than with the other tunnels because according to these investigations, the decision, if needed, will be made to shorten the tunnel from the original design length in the layout if the bedrock characteristics are not favourable for disposal. The reason can be, for example, a hydraulically conductive structure that intersects the deposition tunnel, which then cannot be used for disposal. Nor is disposal allowed at the proximity of the structure and, if the structure continues along the tunnel for a long section, it may be sensible to stop the excavation.

The excavation of tunnels is done with a similar cycle everywhere in the disposal facility. After possible pre-grouting, a tunnel section is drilled, drill holes charged and blasted, the blasting fumes are ventilated out, rock transported away, and the produced section is measured.

After the tunnels are excavated, their surfaces are mapped and, in the deposition tunnels, different measurements are also conducted to discover the possible tunnel sections suitable for deposition hole locations (Saanio et al. 2013).

Openings produced by raise boring

The ventilation shafts and deposition holes are implemented by the raise boring method and full-face vertical push-reaming technique. The implementation of shafts and deposition holes differ in the sense that shafts are widened traditionally from the bottom up whereas the deposition holes on the other hand are widened from top to bottom.

After pre-grouting, the shafts are implemented first by drilling a pilot hole through the selected shaft section that is to be opened. After the pilot hole has been evaluated to be suitable, the drill bit for widening is installed on the device at the bottom and then the shaft is widened to a desired 2.5 metres diameter. The inner diameter for both ventilation shafts is 2.5 m without rock support. Widening can first be made with a smaller diameter bit and again with a larger one.

In the deposition holes, investigation pilot holes are first drilled to ensure the suitability of the location for disposal. Holes are sited using the bedrock classification data and technical requirements, like the minimum distances between the holes. The implementation of the exact hole begins similarly to shafts by drilling a larger pilot hole. After it has been investigated to be suitable, the widening is started from the tunnel floor downwards (Figure 7-8). There is a guide in the widening drill bit that advances in the larger pilot hole and keeps the now widened hole straight. The widened spaces, both shafts and deposition holes, are mapped and investigated as required. The deposition holes are examined more closely than the shafts and, at the end, an assessment of their acceptability for spent fuel disposal as deposition holes is provided (Saanio et al. 2013).

Figure 7-8. Prototype device for boring the deposition holes (Posiva 2016).

7.1.8 Demonstrations

The site confirmation for a detailed repository design and safety assessment include characterisation and demonstration performed underground in e.g. Sweden and Finland. It is assumed that e.g. deposition tunnel and hole excavation, boring and characterization methods are demonstrated at the host rock and disposal depth before the actual production of the Norwegian DGR. A so-called cold test can also be done in the demonstration tunnels.

7.2 Operation

Different types of waste are disposed of in campaigns of suitable duration. Due to technical aspects concerning backfilling it appears preferable to implement the disposal activity campaigns on the basis of waste type. The total amount of seepage water flow is also limited by closing openings as soon as possible after the canisters (or, in the case of the intermediate depth repository, waste packages) have been placed.

In practice this means that first, HLW will be disposed of in the DGR at the depth of 400 metres. The encapsulation and canister transportation outside the National Facility need to be organized so that all HLW is disposed of in one or two disposal activity campaigns. After the HLW disposal, closure will be done for the DGR up to the depth of the intermediate depth repository at 100 metres. The subsequent ILW, VLLW and LLW campaigns are described in Section 6.2.

7.2.1 Activities and schedule

The installation of four fuel canisters and filling up the deposition tunnel for that section takes about 2 weeks (Saanio et al. 2013). It is assumed that with plug production it takes roughly one year to operate the DGR deposition tunnels in the National Facility case.

If it would be possible to outsource the operation services and equipment rental to some other waste company with the same disposal concept, it would affect the timing: it is possible that the NND operation should be scheduled parallel to the other company disposal facility maintenance outage/revision.

7.2.2 Transfer and installation of waste packages

Installation of bentonite blocks in the deposition hole

The bentonite buffer consists of blocks with different heights and shapes (Figure 7-9). The bentonite blocks are transferred to the repository in transfer and installation containers designed specifically for them.

The installation device is driven into the deposition tunnel and stationed above a hole. The buffer block transport shuffle transports the blocks in the transport container one block at a time to the installation device. The gripper in the crane of the installation device grasps the top part of the transport container and lifts it from the transport container. The block is lifted above the deposition hole and lowered down. The block is slowly lowered into the right position guided by the automatic measurement.

The bottom block in the deposition hole is emplaced along with circular blocks up the level of the top edge of the canister, after which the buffer block installation device and the transport shuffle are removed from the deposition tunnel. The installation device is brought back into the deposition tunnel after the installation of the canister and stationed above the deposition hole to emplace the top blocks over the canister (Saanio et al. 2013).

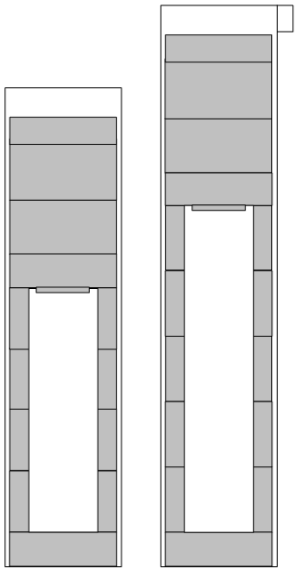

Figure 7-9. Buffer block diagram (Saanio et al. 2013).

Installation of the disposal canister in the deposition hole

In the reloading hall, the canisters are reloaded from the *access tunnel vehicle* to the *canister installation vehicle*. The disposal canisters are transferred from the reloading hall above the deposition hole with canister transfer and installation vehicle.

The canister is placed into the deposition hole using the canister transfer and installation vehicle (Figure 7-6). The vehicle is parked in the correct place above the deposition hole. After this, the vehicle is lifted to rest on its support feet and levelled. When the vehicle is in place, the radiation shield can be rotated to a vertical position. At the same time, the rear end of the radiation shield opens.

When the radiation shield is exactly in a vertical position, the lowering of the canister can begin. The positional lining can be adjusted during lowering if needed. The lowering can be monitored using several cameras in order to ensure that the lowering is successful, and that the canister does not collide with the bentonite buffer rings placed in the hole. Once the canister has been lowered to the bottom of the hole, the gripper can be opened and lifted back inside the radiation shield. After this, the radiation shield can be turned back to a horizontal position and the vehicle can be driven out of the deposition tunnel (Wendelin & Suikki 2008).

Installation of bentonite blocks on top of the canisters

After installing a canister, the buffer block installation device is driven back into the deposition tunnel and stationed again over the deposition hole. The four cylindrical blocks on top of the canister are placed in a similar fashion to the previous buffer blocks.

7.2.3 Backfilling

This section briefly describes an example of the backfilling of the deposition tunnels (Figure 7-10). The main steps are as follows: preparatory work, levelling of the tunnel floor, installation of blocks and introduction of bentonite pellets to fill the space between the blocks and the tunnel walls/ceiling. The logistics of materials and machines as well as quality control of the backfilling operation will also fit in with the operations described above (Saanio et al. 2013).

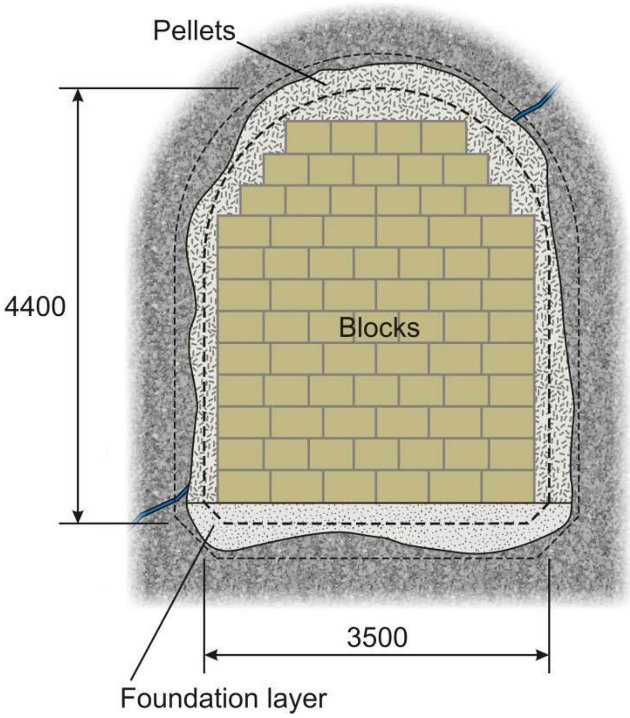

Figure 7-10. An example where the main components of the backfill are backfill blocks, foundation layer and pellets (Posiva 2012c). The theoretical excavation profile of the tunnel is marked in the figure with the inner dotted line and excavation tolerances with the outer dotted line.

Actions before backfilling and levelling the floor

After the canister and buffer materials have been installed, the underground openings are designated as uncontrolled areas regarding radiation protection for the duration of the backfill operation (see Section 7.2.4). However, the measurements for the purpose of nuclear material safeguards will continue.

The ventilation channels, lamps, electricity supply and part of rock reinforcements are dismantled from the tunnel section to be backfilled. Backfill will begin from the levelled rock surface floor where the pellet layer will be installed as a foundation for the backfill blocks.

Installation of backfill

Backfill blocks have been designed to be installed using an automated method (Figure 7-11). The same device will be used also for installing the pellets. Alternative backfill methods are studied for a more industrial way of installation.

Figure 7-11. An example of a prototype backfill block installation device (Posiva 2016).

Plugging the deposition tunnel

When the entire deposition tunnel has been backfilled, a plug structure consisting of reinforced concrete, bentonite sealing layer and a filter will be built at the mouth of the tunnel.

7.2.4 Controlled and uncontrolled areas and phases

The difference between the controlled and uncontrolled area or phase is an issue of being able to measure the radiation doses to which personnel is exposed.

During the canister and buffer installation in the operating phase, the DGR is controlled area. During other work such as backfilling, the DGR is uncontrolled area. This has been incorporated in the licensing documents for the Finnish DGR. The purpose of this division is to control the movements of personnel in an area where there is a possibility of direct radiation and to measure the radiation doses they receive. The whole disposal facility needs to be controlled in another way for safeguarding.

All handling of canisters underground takes place in the controlled phase. The installation of bentonite buffer blocks in the deposition holes before and after the canister is installed also takes place in the controlled phase. The previous excavation and construction work as well as the following backfilling of the openings are done in the uncontrolled phase. During the uncontrolled phase, access is still controlled, but not because of reasons of radiation protection: radiation doses of people are not measured.

Access to the DGR level is by the access tunnel. During the activities in the controlled phase, the whole underground tunnel system is controlled area.

VLLW, LLW and ILW *waste halls* in the intermediate depth repository are controlled area always when there is waste, waste is emplaced there, or waste halls are under backfilling work. This intermediate depth repository is described in Chapter 6.

7.2.5 Radiation protection

The fundamentals of radiation protection and monitoring at the DGR level have been described together with the intermediate depth repository level in Section 6.2.5.

7.2.6 Incidents and accidents

The fundamentals of DGR level incidents and accidents have been described together with the intermediate depth level in Section 6.2.6. The objective is to design the disposal facility so that incorrect operation will not result in an accident. This report does not cover any analysis for incidents and accidents.

7.2.7 Safeguards

Control of nuclear fuel and other nuclear materials required in the operation of a nuclear facility can be assumed to be aimed to ensure that:

- nuclear materials are used, handled, stored and transported safely (safety control),
- nuclear fuel or other nuclear material under Norway's control and of Norwegian origin, or which has been produced in Norway, is not used for nuclear weapons or explosives or for any unknown purposes (safeguards), and that
- sufficient physical protection exists to safeguard the use of fuel and other nuclear materials, their storage and transport against illegal activities (control of physical protection).

Bookkeeping during the disposal operation must at all times hold the information of the nuclear materials at the facilities. Nuclear material bookkeeping and reporting will be governed with a fuel data system developed for this reason. The design basis for the system is not only nuclear material monitoring needs but also aspects concerned with making nuclear waste bookkeeping (for heat optimization etc.) and safety analyses (fuel properties etc.).

Identification and location data of each fuel element to be disposed is validated and documented in all handling stages of the fuel from the interim storages of spent fuel at the reactor sites to the deposition hole. The disposal facility will probably constitute its own material balance area (Saanio et al. 2013).

This report does not cover any detailed plan for safeguards.

7.2.8 Monitoring

The monitoring issues of the DGR have been described together with the intermediate depth repository in Section 6.2.8.

It is important to start baseline studies and monitoring well before the construction activities on the site, so that a sufficient baseline can be established. Monitoring shall be continued during the whole construction and operation phase of the disposal facility, until the time of closure.

The environmental impacts of the project shall be monitored as well as the function of the engineered barriers to ensure that they function as expected. It is also needed to gather data and provide feedback for construction and design on the impact of construction on the geosphere and surface environment.

Monitoring needs to demonstrate that the conditions in the surroundings of the disposal facility remain favourable (resembling the conditions at the site before the disposal facility) for long-term safety despite repository construction, operation and closure. It shall also collect additional information regarding long-term safety critical properties of the site for developing site models and ensuring the suitability of the site.

The monitoring programme can be divided into:

- Engineered barriers
- Rock mechanics (e.g. bedrock movements, rock stress, seismics and excavation-related blasts i.e. safeguards)
- Hydrology and hydrogeology (e.g. groundwater level, flow and pressure)
- Hydrogeochemistry (groundwater chemistry)
- Surface environment (impact and conditions).

7.3 Decommissioning and closure

When all canisters to be disposed of have been emplaced in the deposition holes and the buffer and backfill have been installed, the closing phase of the disposal facility begins. The requirements regarding closure differ from those set for backfilling and plugging of the deposition tunnels. One key purpose of engineered release barriers, such as the backfilling and closure structures, is to limit the migration of radioactive materials via excavated facilities. The backfill materials and closure structures must prevent the formation of significant flow routes between ground level and the deposition tunnels. The backfill materials and closure structures must also support the surrounding bedrock and prevent the inadvertent entry of people into the facilities. In addition to this, the materials used for closure must not have a significant harmful impact on the performance of the multi-barrier system (Saanio et al. 2013).

The closure will be done in two phases. The first closure phase extends from the DGR to the intermediate depth repository level and is done after all canisters are emplaced and deposition tunnels are backfilled and plugged. The second closure phase extends from the intermediate depth repository level to the ground level and is done after all VLLW/LLW and ILW packages are emplaced and all waste halls are backfilled and plugged.

7.3.1 Dismantling work

Closure begins with the dismantling of structures and systems so that harmful quantities of materials are not left in the facility. After that, the facility can be backfilled and plugged using appropriate closure structures (Saanio et al. 2013).

7.3.2 Closure

The closure includes all backfill and closure structures, i.e., plugs, outside the deposition tunnels and the deposition tunnel plugs. The closure of the disposal facility will complete the isolation of the spent nuclear fuel from the biosphere and restore the favourable natural conditions in the bedrock. The closure of the tunnels and other underground openings will prevent the formation of preferential flow paths between the ground surface and deposition tunnel and hole (Posiva 2012b). In the long term, the function of the closure is to maintain the favourable conditions in the bedrock surrounding the spent nuclear fuel. The design for closure of the disposal facility is based on the geological and hydrogeological environment (main fracture zones and hydraulic conductivities of the bedrock) and on the estimations of the permafrost depth in the future. An example of the Finnish closure design is presented in Figure 6-8. Closure of the investigation boreholes is described in Section 6.3.2.

An alternative to emplacing non-radioactive waste in the landfill repository is to use that waste as one backfill component in the lower parts of the National Facility. In that case, some of the openings between -100 m and -400 m levels could be backfilled with the non-radioactive waste, but this needs some further studies to ensure that there will be no harmful interaction between non-radioactive concrete waste and the engineered barriers. If all this concrete waste were mixed with crushed rock 50-50, the mixture could be used for access tunnel backfill for roughly a 650-metre section.

7.3.3 Foreign materials remaining in the facility

It shall be controlled that no significant quantities of materials harmful to the performance of release barriers enter the repositories. The migration of materials detrimental to long-term safety, such as organic matter and oxidising agents, shall be minimised. For this purpose, estimations about the quantities of foreign materials that remain in the disposal facility after it has been closed need to be done.

7.4 Alternative HLW forms

7.4.1 Reprocessed vitrified HLW

In the case of reprocessing the high level waste and receiving vitrified waste form, the decreased waste volume can be fitted in eight Orano canisters. This will affect the number of deposition holes and the length of deposition tunnels. There will also be some changes for buffer and backfill methods.

7.4.2 Reprocessed metallic ILW

If all the spent fuel is reprocessed and only 500 canisters of intermediate level metallic waste is received from Orano, this will result in an increase in the total ILW waste volume. This will affect the volume and length of the ILW hall and concrete basin in it. There might also be some changes for backfill methods and some other engineered barriers too, so the effect of this alternative needs more studies. The preliminary assumption for this description was that a DGR is not needed at all in this alternative, which would considerably change the layout of the National Facility, assuming that the safety of the intermediate depth repository is sufficient for ILW from reprocessing. However, a small fraction of the spent fuel cannot be reprocessed, and it is unlikely that the DGR can be excluded completely.

7.4.3 Non treated HLW forms

Unlike in Finnish or Swedish repositories based on the KBS-3 concept, in the case of the metallic uranium, it cannot be relied on to provide a secondary safety feature through chemical stability of the fuel matrix. This issue may be compensated with additional release barriers in the canister and/or buffer, but exact solutions are out of the scope for this concept description. This alternative waste form is not expected to change the number of canisters or affect the inventory volume significantly.

8 DEEP BOREHOLE REPOSITORY

The deep borehole disposal concept consists of drilling a borehole from the surface of the earth to a depth of several kilometres into crystalline rocks, emplacing waste canisters containing SNF or other HLW in the lower part of the borehole and then sealing the upper part of the borehole. A schematic of the original concept is illustrated in Figure 8-1. Reasons for the selection of crystalline rocks are their high hardness, low permeability and preferable thermal conductivity. The safety case for borehole disposal places also emphasis on the great depth of burial.

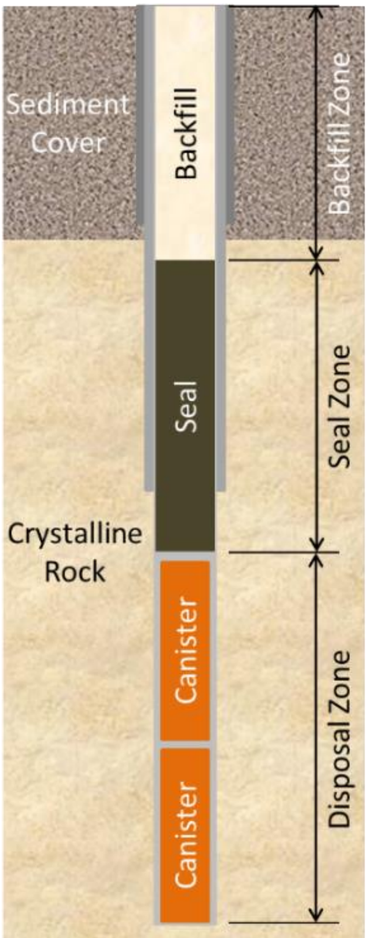

Figure 8-1. Schematic display of the borehole disposal concept.

The following list emphasizes the advantages of the borehole disposal concept.

- Limited surface area is required for the construction and the operation of the facility.
- The required underground space (borehole) volume is relatively low and the drilling process can be carried out in a short time.
- The cross-sectional area of the borehole is small. The geological barrier is hardly damaged.
- The concept is compatible to be used for various waste forms and types.
- Low permeability and long residence time of saline groundwater in crystalline basement rocks suggests limited interaction with shallow fresh groundwater resources.
- Density stratification of saline groundwater with underlying fresh groundwater would oppose thermally induced groundwater convection.
- Geochemically reducing conditions limit solubility and enhance the sorption of many radionuclides.
- The probability of a human intrusion to the borehole disposal facility is extremely low.

The primary advantages of deep borehole could be cost and flexibility (Brady & Driscoll 2010, Bates et al. 2014).

Due to its advantages, disposal of nuclear and radioactive waste in deep boreholes has been studied as an alternative (or complementary) to mined geological repositories. Most of the concepts are based on the disposal of the waste packages in crystalline basement rock. In most cases, a vertical borehole with a depth of around 5 km is assumed mainly because crystalline basement is located beneath a thick layer of sediments or sedimentary rocks.

However, sediments or sedimentary rocks are very rare in Norway. Basically three geological areas can be distinguished in Norway: crystalline basement, mountain belt of the Caledonides and the Oslo Rift. The crystalline basement has an age of about 1700 to 900 million years. Term *Precambrian basement* is also used for this rock formation. This basement rock formed mostly during the Sveconorwegian orogeny. From west to east five segments (Telemarkia, Bamble, Kongsberg, Idefjorden, Eastern segments) are distinguished. These segments are separated from each other by shear zones. The rocks are frequently exposed all the way to the surface in the southern Norway.

The crystalline basement is divided into two areas by the Oslo Rift (Oslo Graben). The rift was formed by lithospheric stretching, associated with igneous activity. It is a high-volcanicity continental rift system. Earthquakes occur, having magnitudes between 2.0 to 3.8, or sometimes greater. The most recent higher magnitude event was a 5.4 magnitude (Richter scale) earthquake in Oslo on October 23, 1904.

The mountain belt of the Scandinavian Caledonides runs along the Atlantic coast. The rocks form nappes that have been thrusted over the older rocks. In addition to the folding, there are numerous shear zones.

Geological disposal facilities are always adapted to the local geology. For the deep borehole disposal, it is assumed that it cannot be built in the Oslo Rift. If a borehole facility is built in the south, a backfill zone can be largely unnecessary. This means that the borehole length can be shortened.

In the north, however, it may be necessary to drill through faults and nappes of the Caledonides in order to have the disposal zone in the crystalline basement. In this case, a deeper hole is required according to the original concept. Also, there are known to be more varying horizontal stresses, which have to be taken into account when planning the casing design of the borehole concept.

As the crystalline rocks are widespread and the amount of high-level waste is limited (e.g. Andreasson 2019), borehole disposal concept is potentially a very feasible option in Norway (cf. IAEA 2017). A borehole could reach crystalline rocks at relatively shallow depth. The low heat flow and thus the low thermal depth gradients in the rock sequences of Norway are also considered to be advantageous. In wide areas of Norway, the seismicity is low. Also noteworthy is Norway's extraordinarily extensive expertise in tunnelling and deep drilling technology. Norway is recognized worldwide as a leader in the advances of offshore petroleum, which relies on drilling of deep boreholes.

Disposal of HLW in Norway has been discussed previously in Metcalfe et al. (2014) and in Mikkelsen & Kristiansen (2019). In addition, Paulley et al. (2014) briefly discuss borehole disposal option. The aim of this chapter is to describe the first borehole disposal concept taking into account the waste quantities and general conditions in Norway. It also investigates the possibility of borehole disposal in more detail. Metcalfe et al. (2014) distinguished two variants of borehole disposal:

- Heat-generating waste is emplaced after little cooling, so that within the borehole sufficiently high temperatures are attained to melt the rock, thereby providing, after the melted rock subsequently cools and solidified, a low-permeability seal.
- The waste is not melted by decay heat and sealing is provided by artificial barriers.

This study only takes the second variant into account. Advantages and disadvantages of borehole disposal are described in e.g. Metcalfe et al. (2014). According to their study, disadvantages are, for example, the immaturity of deep borehole concepts as well as less room in the borehole for overpacks. In this regard, however, it must be taken into account that borehole disposal is also part of several concepts for radioactive waste disposal in mined repositories (cf. DBETEC 2016). An additional disadvantage is the possibility of jamming canisters in the borehole. This chapter considers these issues.

The aim of the first section is to develop a basic concept. Based on information on radioactive waste and canister designs, framework data for the facility is derived. The aim of the individual work sections is to gain input parameters for the further work steps. The processing scheme is shown in Figure 8-2.

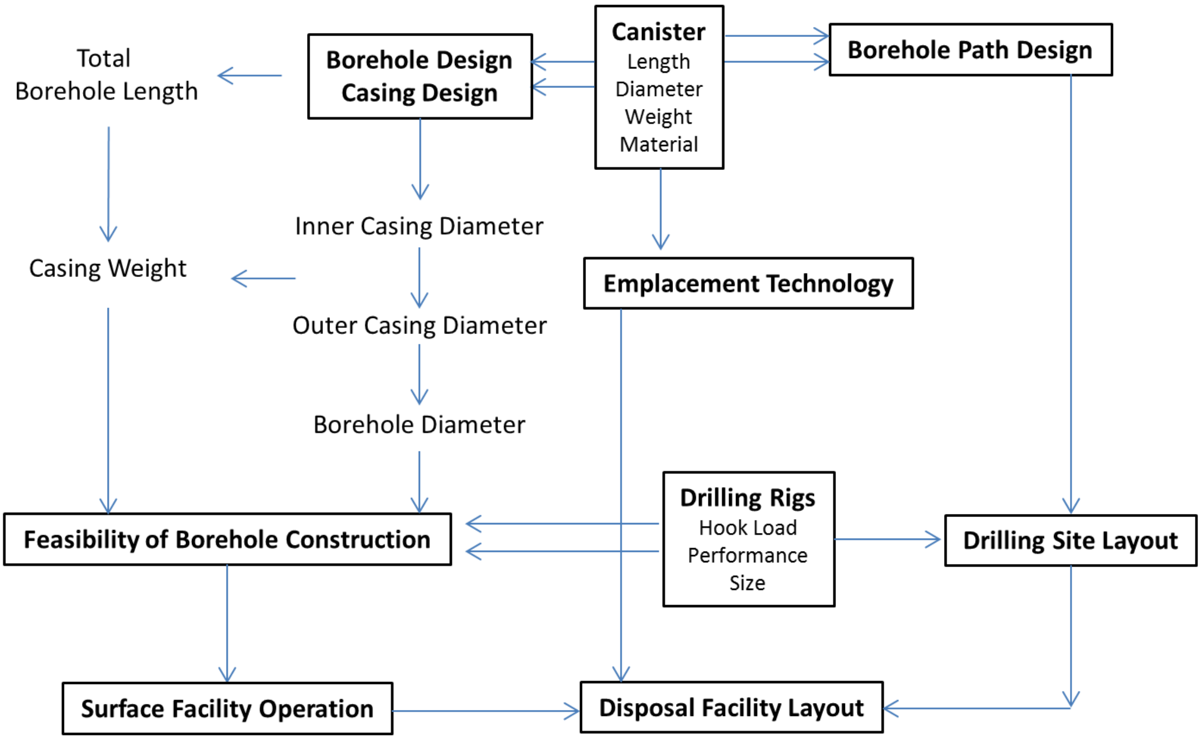

Figure 8-2. Planning stages for the first design of a deep borehole disposal facility in Norway.

8.1 Implementation

The borehole design and construction are mainly dependent on the disposal container dimensions. The larger the diameter of the disposal container, the larger the borehole diameter needs to be. A large diameter of a borehole is a limiting factor when it comes to the depth of the borehole and, therefore, it limits the length of the disposal zone. However, small diameter containers have a smaller capacity. In this case, a large number of canisters results in a deeper borehole. The aim was therefore to identify a borehole configuration that is technically feasible. Larger canisters and thus a lower borehole depth were preferred, so that the emplacement of the canisters can also be technically implemented taking into account the safety requirements. A disposal option with smaller canisters can be implemented as well, whereas the emplacement of the canisters to a depth of several thousand metres is technically more challenging.

8.1.1 Borehole design and construction

Borehole length

The basic concept of a borehole for the disposal of radioactive waste consists of three sections: an upper section in sediments or sedimentary rocks, a seal zone, and the disposal zone in crystalline rock. In Norway, sediments occur only in individual regions. Norway mainly consists of the Caledonian nappes that overlie the crystalline basement. However, large areas occur in the Caledonian mountain chains (orogeny) where basement rock outcrops at the surface. In these rocks, disadvantageous horizontal stresses occur that could be disadvantageous for drilling of a borehole, setting the casing, and the construction of the seal and disposal zone. In addition, the disposal zone should be positioned in rocks where the salinity of the formation waters and their residence time is high, i.e. their mobility low. A major influence on the position and length of the seal zone is the occurrence of rock fractures, in particular their size, frequency and networking. Due to this dependency on the geological framework and the fact that no location of a disposal facility has been selected, no detailed information can be given about the length of the upper borehole zone and the seal zone. However, it is assumed that the upper zone will be significantly shorter compared with the basic concept. Boreholes have a small cross-section and vertical or slightly inclined boreholes can be sealed more easily than horizontal boreholes, where achieving a good and uniform cement job is rather difficult. For this reason, it is assumed that the length of the seal zone can also be less than 1000 metres in the case of favourable geological conditions. As a first rough assumption, a total length of 1500 metres is assumed for the upper zone and the seal zone.

Regardless of the geological conditions, the disposal length depends strongly on the waste inventory and the type of canister selected for the disposal. Bracke et al. (2016) discussed three different disposal concepts. All three concepts are very similar. A borehole of a defined diameter is drilled vertically downward, a casing is set and the canisters are placed in the borehole. See Table 8-1 for the listing of the three concepts.

Table 8-1. Technical data for different concepts in Germany (Bracke et al. 2016).

Concept #	1 * [10]	2 [10]	3 [36,37]
Diameter of borehole	17.5″/44.5 cm	35.4″/90 cm	29.5″/75 cm
Maximum depth of borehole	5000 m	5000 m	3500 m
Disposal zone	3000–5000 m	3000–5000 m	1500–3500 m
Space for cementation	44.5 mm	44 mm	25 mm
Outer diameter of casing	14″/356 mm	32″/812 mm	27.6″/700 mm
Wall thickness of casing	21.6 mm	63.5 mm	62.5 mm
Space between casing and container	24 mm	25 mm	25 mm
Outer diameter of container	265 mm	635 mm	525 mm
Inner diameter of container	175 mm	435 mm	435 mm
Wall thickness of container	45 mm	100 mm	45 mm
Length of container	5.6 m	5.6 m	5.6 m
Number of containers	27,000	11,000	11,000
Number of containers per borehole	180	356	356
Minimum number of boreholes	150	31	31

* Spent fuel rods and pebbles only.

There are some differences, however. While one concept considers a rather small borehole diameter of only 44.5 cm, the other two concepts consider larger boreholes of 75 cm and 90 cm diameter. Other differences in the concepts can be found when it comes to the maximum borehole depth and the casing and canister dimensions. Concept number one considers the small diameter borehole and a maximum depth of 5000 metres with a disposal zone in the lowest 2000 metres of the borehole. Concept number two also considers a maximum depth of 5000 metres. The only option with a shorter borehole is option number three, where the final depth of the borehole is set to be at 3500 m. All three boreholes consist of a 2000-metre long disposal zone. The differences are in the canister dimensions. All of the canisters have the same a length of 5.6 metres. Canisters in concepts 2 and 3 have the same inner diameter but the canister in concept 1 is smaller inside. Concepts 2 and 3 have the inner diameter of 435 mm, while concept 1 has the inner diameter of only 175 mm. The difference in the hole diameter of concepts 2 and 3 is caused by different wall thicknesses of the casing. Also, the space between casing and borehole wall is smaller in concept 3 compared with concept 2. The difference in the number of containers a borehole can hold is fairly significant between concept 1 and the other two.

Based on the Norwegian waste inventory, an estimate for the required disposal length was calculated. The calculation is based on the circle in circle principle and the maximum number of fuel rods or assemblies based on the canister length. With the help of the circle in circle principle, the maximum number of circles with a small diameter r fit into a larger circle with a larger diameter R > r. A more realistic approach would be to leave more space between the waste assemblies in the containers. Still, a simple calculation has provided the first estimates for the required disposal length. The result and the options are presented in Table 8-2.

Table 8-2. Calculation of the required disposal length for different concepts.

			Required disposal length [m]
concept #1	Assemblies per canister (based on the canister length)	14	
	Assemblies per canister (based on the canister diameter)	31	
	Required canisters	522	
	Required disposal zone length		3445.2
concept #2; concept #3	Assemblies per canister (based on the canister length)	14	
	Assemblies per canister (based on the canister diameter)	232	
	Required canisters	69	
	Required disposal length		455.4

For the first concept, the length of the disposal zone is about 3500 metres, and for the second and third options the disposal length is less than 500 metres. There will be no major deviations from these values, even if backfilling material is positioned between the containers or shock absorbers (see emplacement technique). Taking into account the guideline values for the upper and seal zone, this results in estimates for the total borehole length of 2000 and 5000 metres.

Borehole design

Within the past decades, wells have been drilled for several purposes. In most cases, the reason for deep boreholes was the production of oil and gas. With improving technology and a greater focus on costs, drilling engineers started to look for options other than the traditional vertical well. In more and more cases, it was just not possible to reach a reservoir with a vertical well. Typical examples of this are an oil or gas reservoir under a town, a lake or a difficulty to drill the formation. Therefore, technologies have been introduced to reach the reservoir from other surface locations. With time, new equipment and more and more different options came up. Today, the wellbore trajectory can be broken down into three different types additional to the classical vertical well. A basic overview of these three types is illustrated in Figure 8-3.

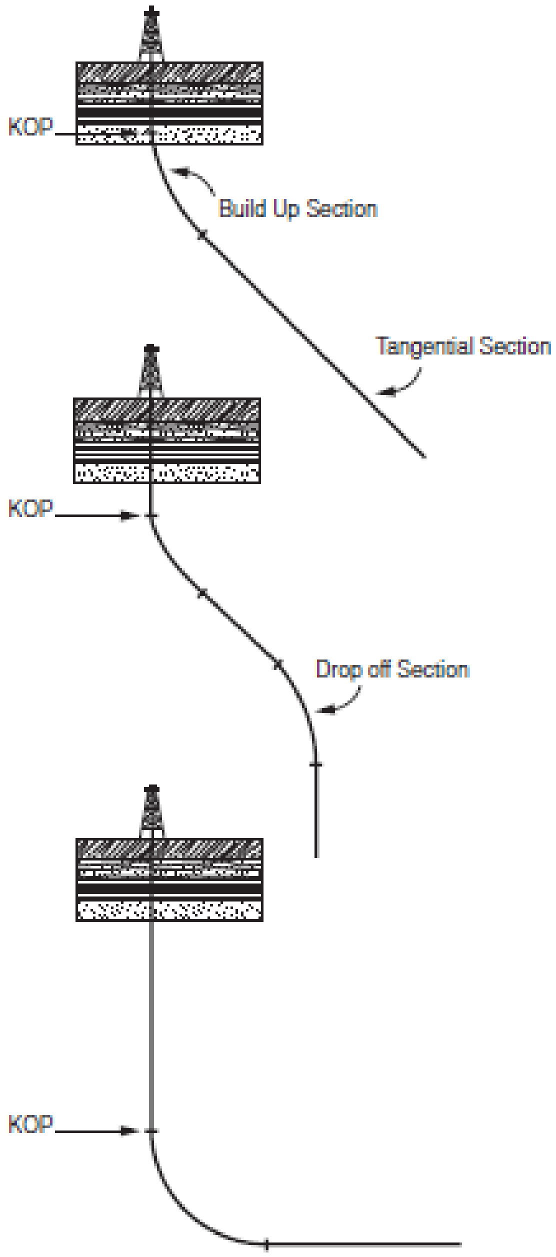

Figure 8-3. Different well trajectories [Drilling Engineering - Hariot Watt University]. Kick off point =KOP.

The upmost part shows the so-called build and hold well type. This means the first part of the borehole is drilled and a certain depth, for example after exiting the groundwater aquifer, the well is kicked off. This point is defined as the kick-off-point. From this point onwards, the well is built up. The length and the angle are different from well to well, depending on the required horizontal displacement and the prewritten well design. Once the required displacement is achieved, the well will be drilled straight again to the wanted target. In the following, this type of well is indicated as a deviated well.

Below the build and hold well type, the s-shaped borehole can be seen. This borehole design is similar to the build and hold design, it only has a drop off section prior to meeting the predefined target. This means the borehole has a vertical part at the beginning and the end with a tangential section in between. Both of these borehole types can be seen as inclined boreholes. The s-shaped boreholes are usually drilled if the subsurface target cannot be reached with a vertical well. Possible reasons are already mentioned before, but also an already existing drill site, which can be used might be the reason to drill this well trajectory. Since the s-shaped drill path does not feature many benefits for the disposal of radioactive waste, it is not included in the upcoming discussion.

The last part of the figure displays a horizontal borehole. Here, the borehole is typically drilled vertical for a long distance until the kick-off-point is reached. Again, a build-up section follows. Once a horizontal tangent can be drawn from the borehole, the path is straightened and the horizontal section of the borehole is drilled.

In the drilling industry, mixtures of the different described options are implemented, but they all come back to these basic types. Each of the different trajectories have positive and negative aspects when it comes to the construction and completion of the borehole. Table 8-3 provides an overview of some aspects, in consideration of using the boreholes as disposal option for radioactive waste.

Table 8-3. Positive and negative aspects of the borehole trajectories.

	Vertical wells	Deviated wells	Horizontal wells
Positive aspects	Easiest to drill and complete Possibility to minimize casing program Disposal and retrieval geometry relatively straight Sealing and backfilling operations less challenging	Several wells from on surface location to different subsurface targets possible Reduced pressure on canisters Possibility to sidetrack Reduced rig hook load	Longest total borehole length Less potential flow path through the borehole (if the horizontal section is slightly upward) No pressure put on canisters by other canisters
Negative aspects	Short disposal zone Potential flow path to the surface through the borehole Great pressure on the lowest canister by overlying canisters Only one borehole from one surface location	Potential flow path to the surface through the borehole Increased torque and drag during the drilling operation	Complicated drilling operation (torque and drag etc.) Cementation and backfilling of horizontal part challenging Disposal and retrieval geometry more difficult (curve radius must be considered) Diameter might be limited

With the same length, vertical boreholes reach the greatest depth, so the highest pressures and temperatures in the borehole can be expected. However, due to the relatively low thermal depth gradient, no major difficulties resulting from the borehole temperature are expected in Norway. Increased pressures can lead to increased requirements in casing design; however, other aspects such as local stresses have to be taken into account. The depth of the kick-off point depends on the geological situation, i.e. above all the thickness of the overburden and must therefore be determined on the basis of the site characterization.

Each borehole trajectory would be suitable for the purpose in Norway. A deviated borehole is the most promising option since it facilitates drilling, backfilling, and sealing with the greatest possible flexibility and offers the possibility to adjust to changing geological conditions. This option combines the elongation of the disposal zone without reaching a true vertical depth deeper than 3.500 metres, but minimizes the risk, which is faced during the disposal phase. In addition, this option keeps the possibility open to drill a second hole from the same site without interacting with the first borehole, if one borehole is not enough for the waste.

To give two examples why the depth and diameter of a borehole are closely linked to each other the flushing of the borehole and the casing weight can be named. During the drilling operation, the borehole needs to be cleaned, which is typically done by flushing. In detail this means that water is pumped through drill string at a high rate. By the power of the water, cuttings and other loose objects are flushed out of the borehole. With an increasing borehole diameter more flushing power is required. At some point the pumps reach a limit, at which the removal of cutting cannot be guaranteed anymore. Still, the second example is more limiting for the diameter of the borehole. Larger borehole diameters require larger casing diameters, which are linked to more material and therefore to more weight. Every rig has a maximum hook load, which it can work with. Therefore, a rig is able to drill to a large depth at a small diameter or a smaller depth with a larger diameter just by the means of the load capacity.

Figure 8-4 shows examples of diameters and depths of existing wells. The red dots in the graphic mark the final depth and diameter of the wells, which set the basis for the red dashed line. This line is a trend line of the already existing wells, to get an idea what seems to be possible at today's technical standards.

The blue vertical lines represent the resulting borehole diameter when a classic design is selected. Each of the three blue lines represents a casing string. The first casing string has a diameter of slightly over 700 mm and a depth of roughly 3100 metres. Next comes a casing of 500 mm diameter to a depth of 4000 metres and finally a 300 mm casing down to 5000 metres. This casing setup simply results from the available data and is only theory to this point. Also, the use of expandable casing is not considered. However, numerous new geothermal and scientific boreholes have not been considered such as the boreholes of the Chinese Continental Scientific Drilling program, the geothermal ST1 borehole in Espoo, Finland or the COSC-1 boreholes in Sweden. Extensive new developments in the field of deep drilling have taken place in the last decades. Of particular note are the powerful hydraulic downhole hammer systems and the development of air borehole flushing. For the future, it can be assumed that there will be a significant gain in knowledge regarding the drilling of large and deep boreholes.

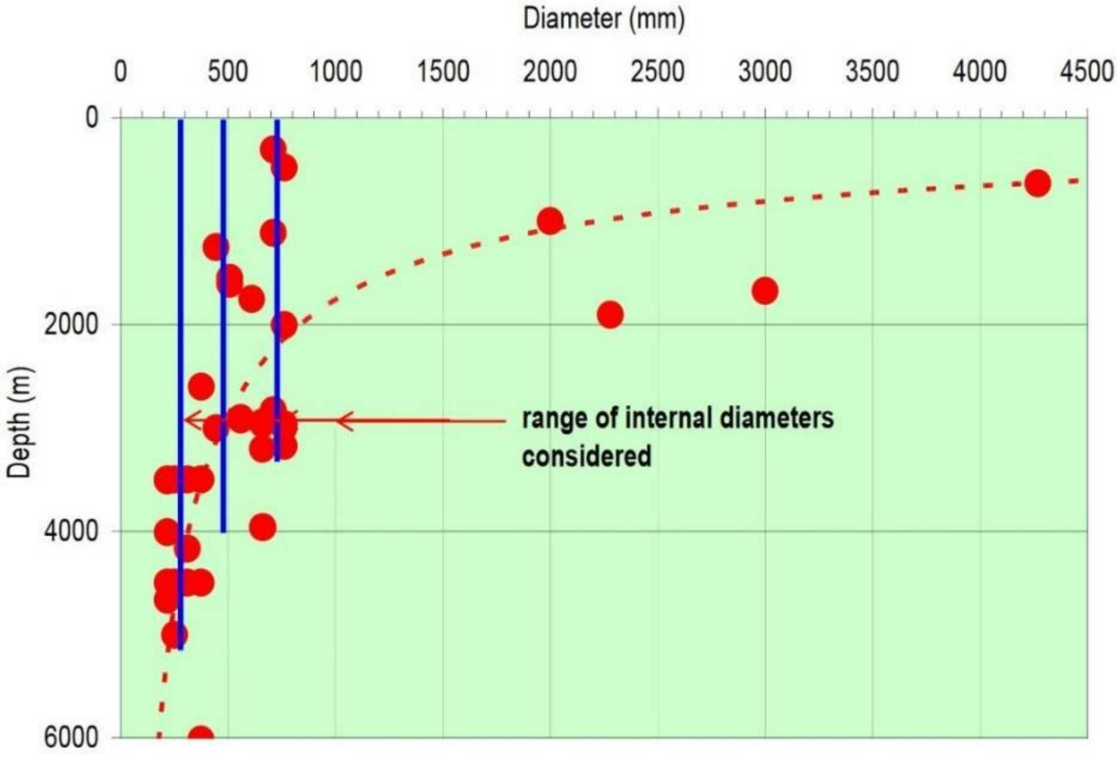

Figure 8-4. Relationship between depth and diameter generated by actual practice according to Arnold et al. (2012) (from Beswick 2008, cf. Beswick et al. 2014). Red dots indicate final depth and diameter of a well. Blue vertical lines depicts borehole diameter for a basic design.

The evaluation of the borehole data as well as evaluation of the performance of modern drilling rigs, (e.g. hook load capacity), showed that boreholes with a diameter of about 700 mm and a length of more than 3000 metres are feasible. No major difficulties were identified. Moreover, this also means more significantly that for Norwegian case one borehole is sufficient to dispose of all the waste. Table 8-4 shows a comparison of the two options. Based on the comparison, larger diameter borehole with a depth of about 2000 metres is considered.

Table 8-4. Comparison of the two borehole options.

Small diameter borehole	Large diameter borehole
Conventional drilling and completion practices can be applied (+)	Shallower operation (+)
Standardized equipment from the oil and gas industry is suitable (+)	Larger canister can be disposed → less canisters required for same amount of waste → less transfers for the disposal operation (+)
Disposal and retrieval operation already tested by Deep Isolation (+)	Suitable canister already designed (+)
Only small canisters fit into the borehole → more canisters required → longer disposal zone → deeper operation (-)	"good quality" formation required (-)
Greater (formation) pressure on the canisters (-)	More challenging technical operation in all respects (-)
Limited possibility to extend the disposal zone by drilling deeper	

8.1.2 Feasibility of the borehole construction

The feasibility test of the borehole can be broken down into individual test steps. In the first step, it is examined whether a borehole of the required length and the required diameter can be drilled. The second step concerns the investigation of the rock quality. Then, it is checked whether the casing can be handled with available drilling rigs. Finally, it is proofed whether the borehole quality is suitable for the disposal of waste canisters.

Several publications (Sassani & Hardin 2015, Nirex Report 2004, Juhlin & Sandstedt 1989) have employed the feasibility of what borehole dimension are possible. These papers and reports showed that the dimensions required for the deep borehole disposal operation in Norway are possible even with an inclined disposal zone.

For the borehole in Norway, it is foreseen to drill an inclined disposal zone. However, the radii of curvature will be large due to the need to transport the canisters (cf. Gibbs 2010). Plotting the values of the actual borehole length or true vertical depth into the diagrams will not lead to any deviating results. The proof clearly shows that a borehole of the required dimensions can be drilled in Norway.

Another aspect that is often concerning during such operation is the rock quality and knowledge about the formation. Because of the mechanical impact during the drilling process and stress redistributions, a damaged zone arises at the borehole contour. In comparison to the undisturbed rock, this zone has a higher porosity, lower strength, and increased permeability. The strength of the rock influences the bond with backfilling and sealing materials, such as the casing cementation. In this case, it is necessary to take into account that the heat of hydration results in additional thermally induced stresses. With the knowledge from the drilling industry and the many wells and the corresponding information in Norway, the rock quality does not seem to be a problem in this project. All the necessary work regarding this topic can be carried out without major problems.

During the borehole completion phase the casing handling system might be critical as shortly described in the following sections. The great loads, which come along with the large diameter casing strings need to be considered and detailed preliminary planning is indispensable. The availability of a rig, which can carry the great loads that can be expected, might affect the operation. If the casing weight can be reduced to a maximum total weight of roughly 450 metric tons, the availability does not need to be considered critical.

Before starting the disposal phase, the completion quality needs to be checked. This is typically done by borehole logging tools. These operations are commonly carried out in the drilling industry and should not have an impact on the disposal project. However, it can be concluded that a quality assured borehole for radioactive waste disposal can likely be implemented according the requirements. Even with the current state of the art of technology, the conditions for borehole disposal in Norway can be presumably created.

8.1.3 Casing design and cementing operation

All existing containers for deep borehole disposal require an inner diameter of the casing of at least 60 cm. With the common casing design specifications, this leads to a hole size of 77.5 cm at the bottom of the hole. By reducing the wall thickness of the disposal casing string this diameter can be reduced. For the project in Norway, this might be a possibility, since stable formations are expected, and no extreme pressure zones or geological movements are expected. Compared with the lifetime of the casing in an oil or gas well, the relatively short operational time has a positive effect on the casing wall thickness, since a thinner casing wall might be sufficient as well. As a conservative approach, the casing setup presented in Table 8-5 has been selected. In the drilling industry it is hard to exactly plan the well up to the meter, therefore only rough values can be given. With more data regarding the pressures and the geology of the final location, more detailed planning can be carried out. The numbers presented are based on similar operations. Adaptations or changes are likely once the final location is chosen or in some cases even during the drilling itself. Not only can the casing setting depth change later, but also the casing scheme might change. In complicated formations with many different pressure regimes or aquifers, more casing strings might be required. Hence, the best possible knowledge of the geology and formation is required before drilling starts. On the other hand, a reduction of casing strings might be possible as well.

Table 8-5. Casing setup for the disposal project in Norway.

	Casing (outer) diameter [mm]	Casing setting depth [m]
Conductor pipe	1500	15
Surface casing	1250	~ 400
Intermediate casing	900	~ 1800
Disposal casing	700	3500

Another topic that needs to be mentioned is the maximum weight of the casing string. For the rig selection, this plays an important role. During any drilling and completion operations the casing is the maximum weight put on the rig. Again, the large diameter borehole plays an important role. Since standard casings are available in these large dimensions, a calculation of the largest common casing on the market has been carried out. Even this 20 inch casing with a wall thickness of 0.64 inch has a nominal weight of 133 lb/ft. Considering this casing for a borehole depth of 3500 metres, the casing weight will be almost 700 tons. Most of the common heavy drilling rigs have maximum hook load of 450 tons. Still, there are rigs available that can hold these loads. These rigs are relatively rare and many projects like the German Continental Deep Drilling Program and the Kola Superdeep Borehole have used specially designed stationary rigs. To avoid these additional high costs, there are options to reduce the maximum load such as:

- Reducing the wall thickness
- Using another light material (e.g. aluminium)
- Using a liner system for the disposal casing string

As there is no detailed information on the local geological conditions it is not possible to provide casing design. Once more information exists, the design and calculations for the casing can be made relatively fast.

8.1.4 Casing cementation

For the operation of the disposal borehole, a solid bond between the casings or liners with the rock formations is required. With the aim of holding the casings in place, it may also be necessary to seal and stabilize loose or loosened rocks. With regard to their long-term stability a favourable chemical environment is to be guaranteed. In addition, movements of fluids along the borehole should be largely restricted, in particular to prevent or at least to limit corrosion processes. These tasks are performed by materials that are pumped into the voids, where they harden to low-permeability solids. The commonly used cementing materials from the oil and gas industry can be one option. The recipes for these materials usually contain cement according to EN ISO 10426-1. But the cement around the disposal zone will face high temperatures and here an additional sealing ability of the material will be beneficial for the operation. With regard to the long-term stability of the materials, it should also be pointed out that the radioactive heat generation leads to a temperature rise above the temperature of the building material, which was achieved during hardening (cf. Lorenz et al. 2015). This can lead to dehydration of mineral phases. However, it can be assumed that the tests of applicability result in suitable recipes, especially since there are extensive application rules for the development of temperature-resistant building materials and their use.

8.1.5 Drilling rigs and drilling site

All drilling rigs have a similar setup and consist of five different systems, which are necessary for the drilling operation. These systems are:

- the hoisting system
- the power system
- the circulation system
- the rotating system
- and the blowout prevention / well control system

Each of the systems consists of defined parts and has certain functions. The arrangement on the drilling site itself can be varied and fit to the available space and shape of the area.

The most noticeable part of the rig is the derrick. The derrick, also referred to as the mast, is the main part of the hoisting system. In addition, the derrick is the highest part of the rig. The height of the derrick gives a rough estimate for the size of the drilling site. According to the German Deep Drilling Ordinance (BVOT) §18, the centre of the well needs to have a minimum distance to the nearest building, public traffic facility and similar to be protected objects of at least the mast height times 1.1. (2006, BVOT §18). Each country has their own building codes, regulations and laws. It is advised to check what is said in the Norwegian legal framework about drilling operations and site requirements.

For the rig selection, the main factor is the maximum hook load. For this reason, many rigs are named after the maximum load they can carry. During the drilling and completion phases, typically the greatest load is the casing weight of the final string. Therefore, this load plays a major role during the rig selection process.

8.1.6 Safety classification

Systems, structures and components of a nuclear facility are grouped into safety classes. The safety class provides the basis for defining the quality assurance requirements for the systems, structures and components of a nuclear facility. Safety classification forms the basis for determining the scope of regulatory controls by the radiation authority. Safety classification system is not explored more detailed in this report.

8.1.7 Fire safety

With regard to fire safety, all requirements of the building laws and deep drilling technology will be taken into account. Time periods of construction (well drilling) and operation of the disposal facility should be considered separately. One reason is the use of the drilling rig during the first stage and the fact that the drill bit reaches rocks whose properties are not yet fully known. During the operation of the facility, an emplacement device is used instead of the drilling rig. In addition, the presence of radioactive waste is taken into account.

An important basis for the planning is American Petroleum Institute (API) (2019). The layout, design and construction of the facility will be made in compliance with local building code and other relevant regulations in Norway.

8.1.8 Facility adaptation for different waste volumes

The borehole disposal facility is designed for the currently expected waste volumes in Norway. The facility consists of one deep borehole for the disposal of HLW. The capacity of the borehole facility can be adjusted to different waste volumes by adjusting the borehole length and/or drilling additional boreholes from the same surface footprint.

There are basically three ways to expand the capacity of the facility.

1. Deepening the borehole.
2. Drilling of a second disposal zone by means of sidetracking from the existing borehole, or
3. Drilling of a second, new, borehole.

The possibility of deepening the borehole depends on the depth and the quality of the geology. With the usual depths of the borehole sections that are needed for sealing and backfilling, the feasibility of this option is considered low.

Sidetracking from the original borehole is a common drilling technique, which reduces the total drilled depth. Drilling a sidetrack is often more challenging compared with drilling a completely new hole from the surface. Piloting the right hole, either the original hole or the sidetrack, during the disposal phase can be rather complicated. Using a whipstock to kick off the sidetrack after the original hole is completed and the disposal operation of this part is done, could overcome this challenge. Having both holes open at the same time would lead to an unnecessary complicated operation. The second option (sidetracking) is potentially feasible in the case when disposal operations in the original hole are finished. The third option (new hole) has the disadvantage that an additional pathway is created from the surface (biosphere) to the host rock of the disposal zone.

8.1.9 Facility construction in phases

The deep borehole disposal facility is constructed in a single phase. Prior to the construction comes the planning phase and once the construction is completed, the disposal operation starts. Preparing the drill site, the actual drilling operation and the completion are all carried out one after another in the construction phase. Since the drilling and completion take turns during the construction phase, no distinction and differentiation into different phases are made.

8.1.10 Demonstrations of borehole disposal operation

It is assumed that borehole drilling and characterization methods are demonstrated at the relevant host rock prior to the construction of the facility. In addition, disposal operation (container placement) is demonstrated in a comparative environment prior to the operation phase of the facility.

8.2 Operation

8.2.1 Activities and schedule

The life cycle of a waste disposal facility is divided into several phases and sub-phases that can overlap in time. Figure 8-5 below provides an overview over the different phases. Currently, on the duration of the individual project periods or phases nor assured level of knowledge is available that is based on practical experiences in the field of deep borehole disposal. However, information on the schedule can be obtained on the basis of planning data.

Each of the three phases is defined by different aspects and has influencing factors. During the pre-operational phase, the design and construction operations have a huge impact on the costs and time. Depending on the depth and complexity of the borehole the drilling time will vary. The HG-1 well in Iceland was drilled to a depth of almost 2500 metres in less than 45 days (Pálsson 2017). Other wells took up to a year or more to be drilled.

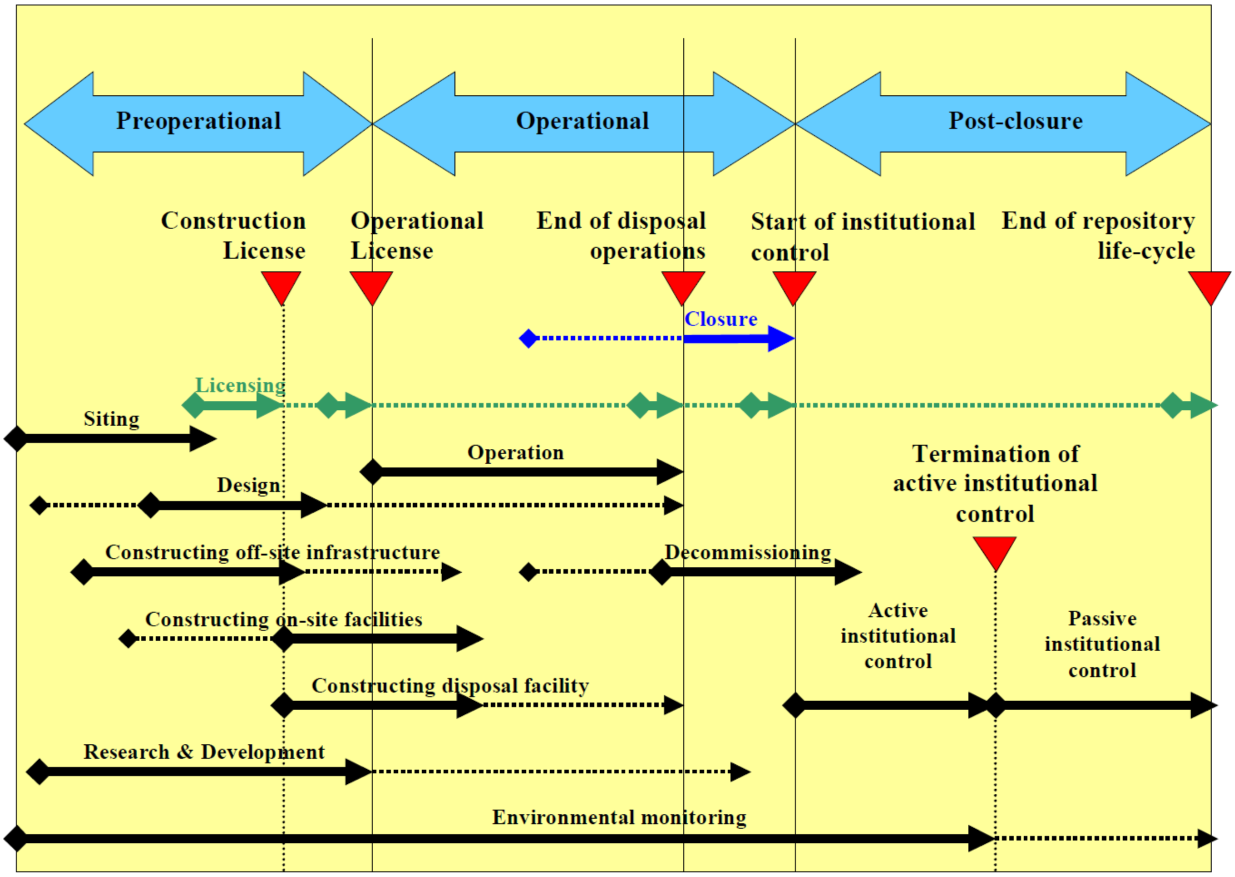

Figure 8-5. Life cycle of a disposal facility divided into phases according to IAEA (2007).

The drilling time is influenced by many factors. A typical time versus depth diagram is presented in Figure 8-6. Each of the operations pointed out has an influence and in case something unplanned happens, the operation will take longer. During the construction of the borehole different operations are carried out. In some operations, rock core is required for characterisation of the geology and therefore certain parts of the hole is cored. This typically takes longer than conventional drilling and helps to get a better understanding of the geologic formations. Figure 8-6 also gives an indication of the drilling technique by mentioning directional drilling. Directional drilling simply means that a well is drilled out at an angle. The well is drilled with either a steerable downhole assembly or a rotary steerable motor (Hyne 2012).

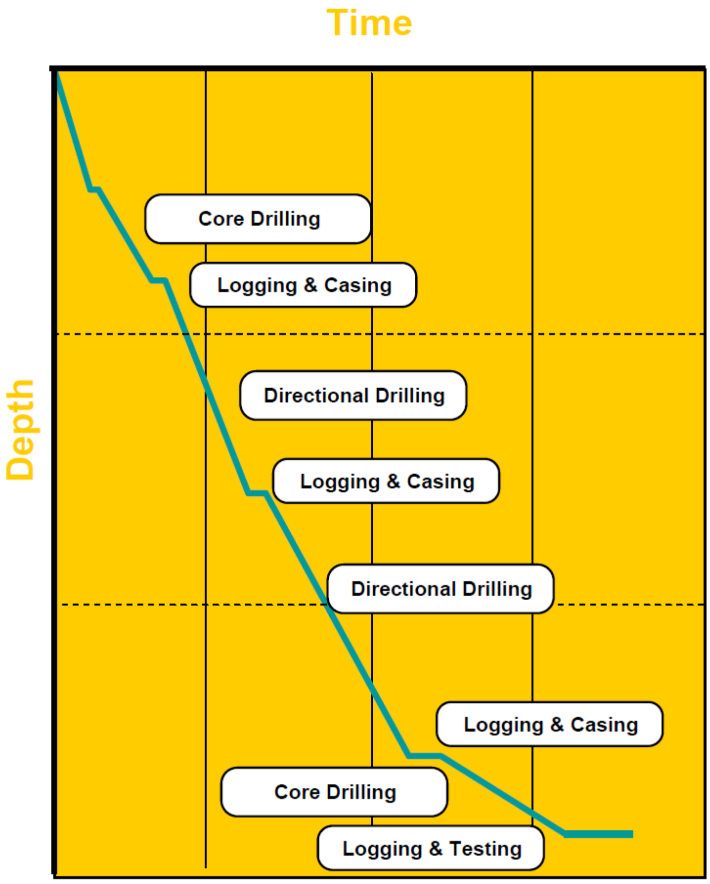

Figure 8-6. A typical time versus depth diagram for an evolving and maturing drilling project according to Harms (2015).

Most of the activities required for the commissioning of the borehole disposal facility can be carried out simultaneously with the boring of the hole. These include the erection of buildings, measuring devices of the monitoring and surveillance program, etc. Work that can only be carried out after completion of the borehole and therefore is decisive for the time of the pre-operational activities is the removal of the drilling rig, the construction of the unloading hall, the installation of the emplacement device and its housing. It is estimated that one year is sufficient time from the beginning of the drilling operations until the first waste package is delivered. This time excludes any extra time potentially needed for regulatory aspects. If the construction and operation of the borehole disposal facility could be achieved under a single licence process that would streamline the schedule.

The duration of the operational period depends on the number of canisters and the duration of the emplacement, whereby this time span depends primarily on the schedule of transport. In addition, tests of the emplacement technology, such as with dummy canisters must be taken into account. The backfilling of residual cavities requires additional work as well as the performance of borehole measurements. Finally, repair and maintenance work on emplacement-relevant devices must be taken into account. Other work such as the duration of the acceptance control or the unloading and unpacking of the canister, however, are of secondary importance because they can be carried out at the same time as the emplacement device is in operation. The time span of disposal ends with backfilling measures or the setting of plugs as well as final control measurements. It is estimated that this work will require two months. The uninterrupted execution of the work always requires timely planning of the work in preliminary work phases. In any case, the work in context with waste disposal should be completed in one year.

Finally, the post-closure period includes measures of institutional control. These measures can be divided into active and passive controls (e.g. IAEA 2009, IAEA 2011, chapter 5.6). Active controls are for example restrictions on access, post-closure environmental monitoring, surveillance and remedial work, e.g. maintenance of vegetative covers. Passive controls are restrictions on land use and record keeping.

The type and duration of the institutional control measures depend in particular on the possibility of a human intrusion, which decreases with increasing depth of the effective containment zone (barrier system) and its decreasing footprint. In the case of deep borehole disposal, the risk of human intrusion is very low. Active institutional control is not absolutely necessary. However, it could make sense to drill an investigation borehole near the effective containment zone. Other deep holes must be prevented. Due to this fact the area of the facility should continue to be state-controlled. Moreover, due to the long half-life of the disposed radionuclides, information should be retained for as long as possible to provide a basis for any future decisions concerning the site. On this basis, regulatory agencies can refuse to permit deep drillings near the facility.

8.2.2 Repository operation

Borehole disposal requires surface facilities such as disposal hall structure and an emplacement device. Research and development of the emplacement technique is central because the suitable technique is indispensable prerequisite for the implementation of the deep borehole disposal facility. The disposal technique is based on concepts from borehole disposal in excavated repositories (e.g. Bollingerfehr et al. 2011). The concept also relies on the experience from the deep drilling industry. In borehole disposal there are requirements for a remote, personnel-free operation and higher weights of the waste canisters compared with probes in oil and gas industry. Knowledge of shaft conveyor systems is also valuable. One peculiarity – which may need additional background research – is the requirement that canisters of high mass have to be transferred to great depths. In addition the required reliability of the emplacement technology with the proximity of almost unshielded waste canisters. Four principle emplacement mechanisms are described (cf. Arnold et al. 2013, Beswick et al. 2014, NWTRB 2016) and listed below.

1. Free fall
2. Wireline
3. Use of drill pipes/drill strings
4. Use of coiled tubing systems, and
5. Conveyance liner.

Figure 8-7 illustrates the emplacement into a fluid-filled borehole using a wireline, drill pipe or coiled tubing system. The housing of the emplacement device is required in order to ensure radiation protection.

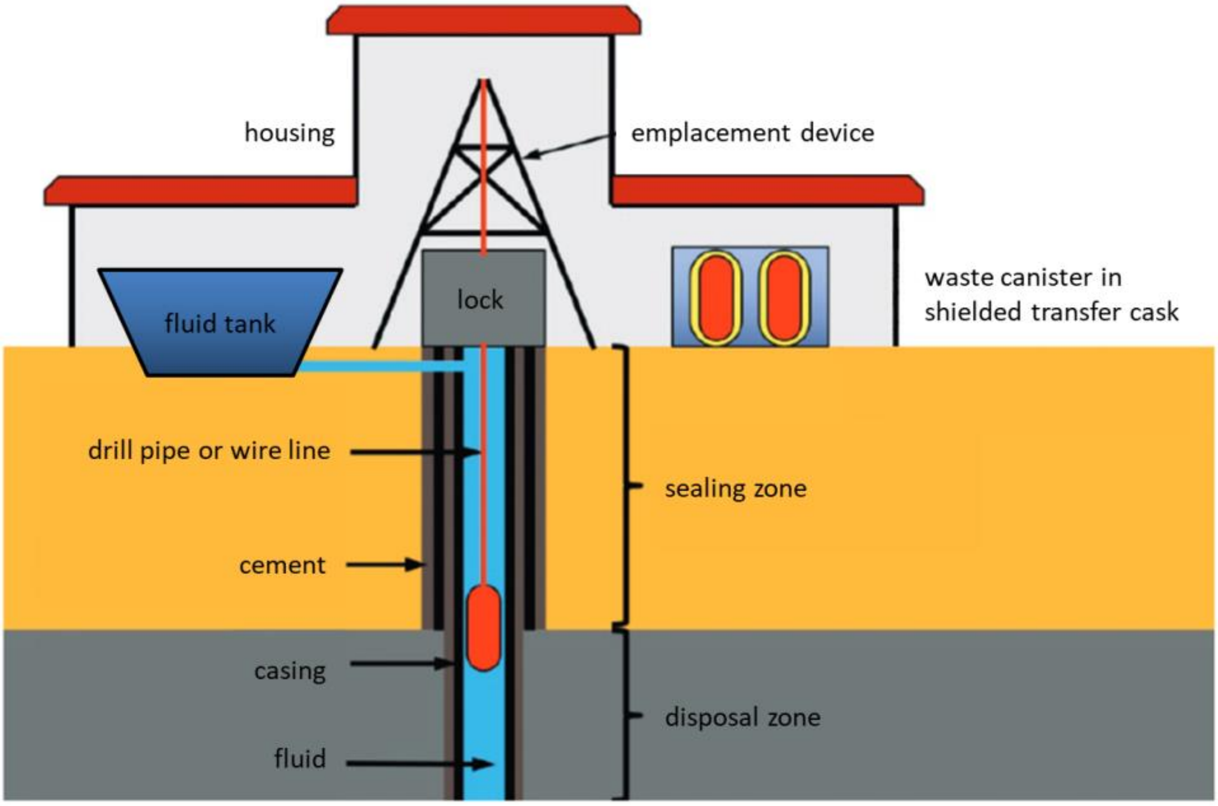

Figure 8-7. Schematic of emplacement of the disposal container according to Rosenzweig et al. (2019).

The preliminary analysis of emplacement technologies indicated that wireline and drill strings are potentially suitable for the disposal operations in Norway. Some modifications are required, which also will depend on the selected canister. The statement applies in particular to single emplacement of canisters, comparable to the BSK3-canister. However, an emplacement waste canister strings or batches were also considered by previous studies (Arnold et al. 2012, 2013, Gibb et al. 2008, cf. Gibb et al. 2012). This option is not considered here further. According to previous calculations, the duration of the emplacement phase of a borehole facility is relatively short compared with the total duration of the project. Thus, the time saved during emplacement would not justify the additional development effort. The number of round trips can also be reduced by choosing canisters of a larger capacity.

8.2.3 Waste packages

There exist several canister options for borehole disposal. Canisters differs in size, shape, mechanical stability, and material. The so-called Brennstabkokille (BSK) is specially designed for the disposal of used nuclear fuel rods in boreholes. The container is made out of stainless steel or as a variant with copper (GNB 1998). Bracke et al. (2016) describes the so-called DBC-R canister variant that has almost the same dimensions as the BSK-R canister. Both canisters have a feature on the top to implement retrievability option for the canister. Hence "R" in the canister name. Moreover, BSK-R and DBC-R are slightly conical and not cylindrically shaped. Table 8-6 summaries the dimensions of selected disposal canisters. Figure 8-8 illustrates some of these designs. Other canisters designed for borehole operations are described in Hoag (2006) or Rigali & Price (2016). So-called HAW canisters are smaller and combined to in packs of three to be placed into an over pack, which is a cylindrical body with a rather small wall thickness.

Table 8-6. Dimensions of disposal containers.

	Outer length [mm]	Outer diameter [mm]	Inner length [mm]	Inner diameter [mm]	Mass [kg]
BSK	4980	430	4550	350	-
BSK-R	5060	520	4845	431	-
BSK 3	4980	≤ 440	-	-	5226
DBC-R	5600	640 to 740	-	435	Up to 15000 (when filled with fuel rods)
KBS-3	4835	1050	-	-	Up to 25000 (when filled with spent fuel)

For the disposal operations it would be beneficial to have larger diameter canisters. This would mean that more fuel rods could be loaded in a single canister and therefore fewer canisters needed. Which then imply that the borehole could be shorter. In the current borehole design the inner open diameter (free space inside the casing wall) is about 600 mm. The disposal operations would require some free space (tolerance) and hence the maximum outer diameter of the canister is about 520 mm.

A major concern when it comes to the material selection is the resistance to corrosion. Copper has been investigated for more than 20 years (King et al. 2002). In addition, to Sweden disposal programs in the UK (NDA, 2010), Canada (Maak 1999), Switzerland (Johnson & King 2003) and Japan (JNC, 2000) have been adopted copper as their material of choice. This makes the retrievable, copper BSK-RCu canister most suitable for the operation, in particular because borehole disposal has already been tested with BSK.

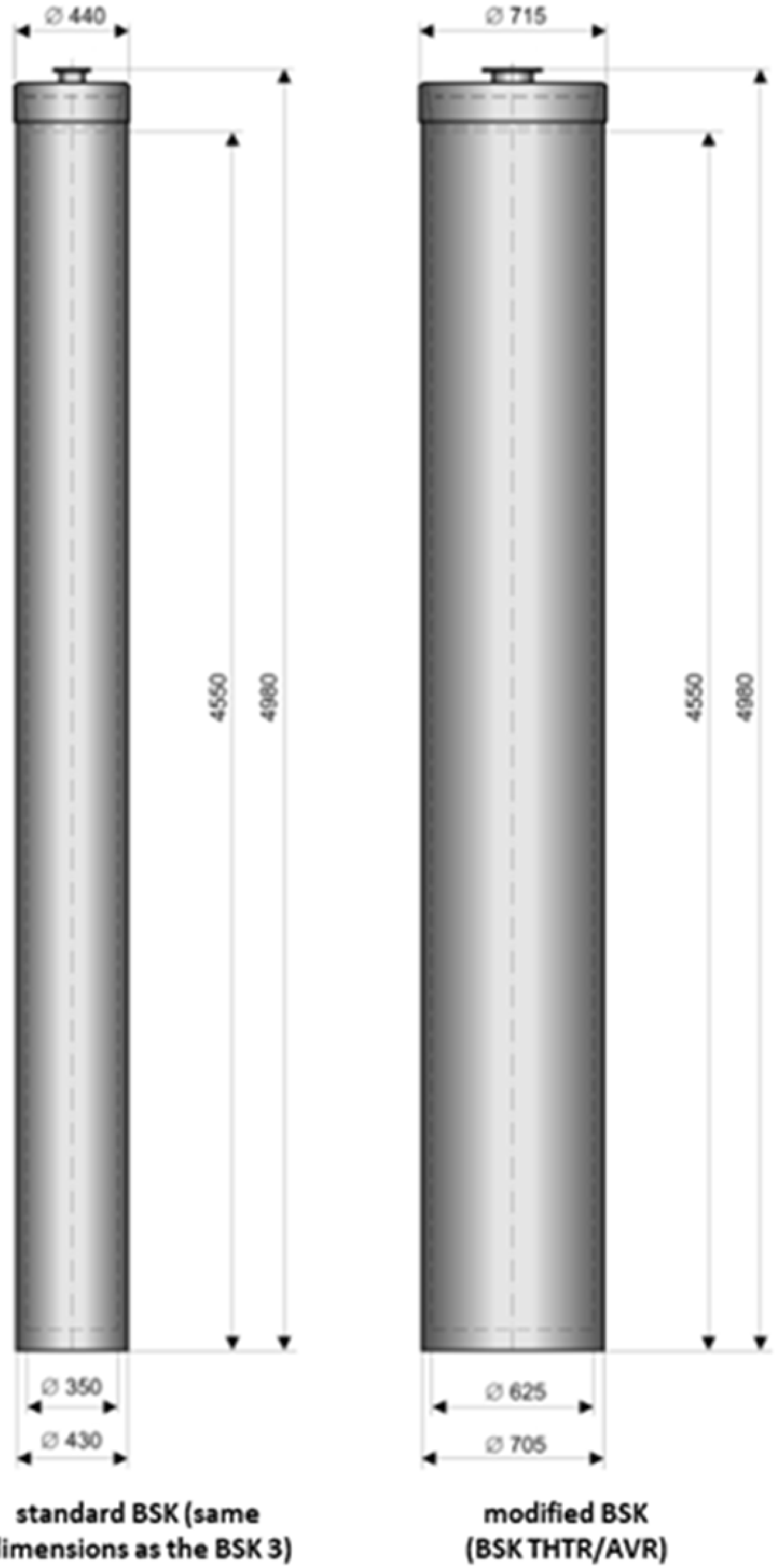

Figure 8-8. Different disposal containers.

8.2.4 Radiation protection

The purpose of radiation monitoring is to measure and monitor the activity of disposal facility air and the radiation doses received by personnel. Employees are potentially exposed to radiation doses emanating from the waste packages. The periodic services, maintenance and cleaning, which take place in the disposal facility, normally cause no radiation doses to personnel.

8.2.5 Incidents and accidents

The objective is to design the borehole disposal facility so that incorrect operation will not result in an accident. This report does not cover any analysis for incidents and accidents.

8.2.6 Safeguards

Safeguard will ensure that the handling of nuclear material is controlled and handled in the purpose of disposal. This report does not cover plans for safeguards.

8.2.7 Monitoring

To ensure that facilities are operated and activities conducted so as to achieve the highest standards of safety that can reasonably be achieved, measures have to be taken to control the radiation exposure of people and the release of radioactive material to the environment (IAEA 2017, see also IAEA 2010).

According to IAEA (2003, chapter 5.3.9) monitoring and surveillance are important for public and technical reassurance. Monitoring programs need to be designed and implemented so as not to reduce the overall level of long-term safety. A program of surveillance and monitoring should form part of the safety case.

In general, monitoring will be required during each phase of disposal facility development:

- To provide reassurance to stakeholders including members of the public that the facility is performing as planned;
- To record or confirm the system description, to provide information for safety assessment and to provide baselines against which any changes can be assessed;
- To assure satisfactory conditions for the safe continuation of the current stage, including that doses to workers and members of public remain within design constraints and safety limits;
- To provide information to confirm the understanding which underlies a previous step or enhance the technical confidence to take the next step in the phased development of a borehole facility, or to identify reasons to delay or amend plans;
- To give an appropriate level of confirmation of the results of assessment calculations.

In general, the procedures cover

- radiological monitoring with respect to the safety of the staff and environment and
- monitoring of the effects of the operation of the disposal facility on the environment.

During the design or construction phase of a borehole facility, background data should be collected as a pre-disposal benchmark, and used as reference levels (cf. Posiva Oy 2012). The results of pre-disposal monitoring will assist in building confidence in the safety and long-term performance of the facility and assist decisions for its future development. According to IAEA (2003) the data might include gamma radiation fields, radionuclide content of the dust, radon–thoron concentrations and radionuclide content of the soils, water and air on site. Facilities containing deep boreholes could be monitored for potential releases through the nearby water bearing horizons, although releases of activity are not anticipated to occur (IAEA 2003c).

According to the German atomic law, radiation protection law and other regulations, disposal of radioactive waste in deep boreholes requires the same monitoring efforts as in the case of disposal in a mine. The disposal and monitoring in the operation phase have to be done according to the requirements of the Nuclear Safety Standards Commission and radiation protection standards. These standards include hot cell conditions and remote handling techniques, as during the disposal procedure the canisters are unshielded. All disposal operations at the site of the borehole have to comply with the general requirements:

- Every canister must have a unique identification number (ID).
- The tightness of the canister has to be ensured.
- The stress levelling of canister has to be given.
- Any deadlock must be manageable for retrieval.
- The contamination of tools must be checked.
- The conditions in the borehole must be monitored until closure.

Parameters to be monitored are amongst others the humidity, the temperature, the radiation field, gas generation and composition.

In the Euratom 7th Framework Programme, the project MoDeRn addressed monitoring of a mined repository and it was aimed to provide a reference framework for development and possible implementation of monitoring activities during disposal processes. In this project the following parameters were identified to be monitored:

- Temperature.
- Mechanical pressure.
- Water content and humidity.
- Hydraulic pressure.
- Radiation.
- Displacement.
- Gas concentration (O_2, CO_2, H_2, CH_4).
- Gas pressure.
- pH value and redox potential (Eh).
- Concentration of colloidal particles.
- Alkalinity.

If the use of a tight casing or liner is foreseen to provide a dry borehole, then the tightness of the casing or liner has to be monitored regularly during the disposal operation. Any fluid has to be detected in order to prevent corrosion of the canisters. Any contamination in the gas phase, (e.g. fission gas Xenon) has to be monitored. If the casing is perforated in the disposal zone, then the borehole could be wet and a metal corrosion with hydrogen generation could occur. Depending on pressure evolution, the stability and corrosion resistance of the canisters, a contamination of fluids is possible and has to be monitored.

Due to the special framework of borehole disposal, for example the depth of the disposal zone and the small cross-section of the borehole, it must be checked precisely to determine which measurements can be carried out, make sense, and at which locations the investigations should be carried out. IAEA (2003) describes that the regulatory body should provide guidance in order to establish the monitoring program, including monitoring of releases and external exposure, and to assess the environmental impact of construction, operation, closure and post-closure activities. The regulator body should ensure by inspection on the site that the operations are carried out in accordance with established procedures as specified or referred to in the relevant licence or authorization and in existing regulations. The operator ensures by means of monitoring measures that the requirements established by the national authorities are met. In addition, the regulators or another independent body may carry out an independent monitoring program as a measure of public reassurance.

8.3 Decommissioning and closure

8.3.1 Dismantling work

Decommissioning include removing any surface structures and systems that are not needed after the closure in the facility.

8.3.2 Closure

After successful disposal of the waste packages and the proof that no radionuclides are released from the borehole, the facility's closure phase can begin. Information about this phase can be found in IAEA (2003, 2009, 2011). It can be roughly divided into the sub-phases of decommissioning, backfilling and sealing of the borehole and site rehabilitation.

The objective of decommissioning is the release of the site from the nuclear regulatory control and the removal of physical infrastructure that are no longer required. Initially contaminated materials or tools are removed, and technical facilities are decontaminated so that the working area is cleared. The clean area should then be monitored to see if the level of radioactivity has sufficiently decreased, thus, a radiation-controlled area is no longer required. The improved accessibility of the site simplifies the following work steps, such as the removal of unneeded infrastructure in order to improve the spatial framework for the backfilling and sealing activities. This will affect in particular remaining parts of the emplacement device. However, depending on the technology, it could be possible that parts of the system can be used for the backfilling and sealing activities. In this case, the modification of the system takes place. Due to the extensive experience in dismantling nuclear facilities, this work can be carried out without any major problems.

If sufficient favourable framework conditions have been created, technical equipment for sealing and backfilling can be installed. With these activities ends the possibility of simply retrieving the waste packages. The seal should consist of several elements with different materials and a functional diversity and redundancy should be realized, where the sealing is based on different mechanisms. Materials that are suitable according to the available experience contain clay, (bentonites or mixtures with bentonites) and cement (grouts, mortars or concretes). These materials should be arranged one behind the other in the direction of flow of fluids in order to avoid degradation of clay minerals. In relation to long-term stability, the cement-based materials should contain reactive additives. This has the positive effect of lowering the pH, so that the risk of clay mineral degradation is reduced. Aggregates can be used to reduce the heat generation during hardening, so that the risk of thermally induced cracks is reduced. As a third element, a borehole section can be filled with bitumen or asphalt. Seals of this configuration are described in several publications, for example Arnold et al. (2011) and Rosenzweig et al. (2019).

Often a greenfield state is the final aim. This means that all facilities and buildings are removed and the site is restored to its natural condition. However, a number of other objectives are feasible, for example, the industrial use of the site or reuse of remaining buildings. Particular attention should be paid to institutional control. Consequently, the extent and type of rehabilitation measures (cf. IAEA 2011, chapter 5.5.2) depend on the planning for the use of the site. Rehabilitation will usually include the removal of

- buildings, such as also garages and roofed places, parking lots, roadways, walkways,
- water and electricity supply and infrastructure for communication,
- fences and lighting devices,
- and the removal of waste/surplus materials and debris.

Additional work comprises the levelling of the site to its natural grade and restoration of vegetation. All these tasks are common practice in the civil engineering industry and can be done easily.

8.3.3 Institutional control period

The final phase is the institutional control period. This consists of a wide range of measures and can be assigned three main objectives:

- Preventing a damage of the barrier integrity (technical and geological barriers).
- Checking the function and thus effectiveness of the barrier system, and
- Passing of information, knowledge and skills from one generation to the next.

8.4 Alternative HLW forms

8.4.1 Reprocessed vitrified HLW

In the case of reprocessing the high-level waste and receiving vitrified waste form, the decreased waste volume can be fitted in eight Orano canisters. This will have an effect on the length of borehole, which can be shortened significantly.

8.4.2 Non treated HLW forms

The alternative where no treatment of the metallic uranium takes place is not expected to change the number of required disposal canisters or have an effect on the inventory volume significantly.

9 LANDFILL REPOSITORY

9.1 Implementation

9.1.1 Landfill repository design

General design basis for the landfill repository and site conditions are discussed in Section 2.1.4. The basis for dimensioning of the repository is discussed in more detail below.

Dimensioning of the repository

The dimensioning of the repository is based on waste masses identified for concrete and soil, other non-radioactive decommissioning waste (inflammable, non-hazardous and non-radioactive) and hazardous waste ranging from 33,000 t up to 60,000 t (Table 9-1). Note that the dimensions represent the area occupied by the waste and the actual area to be reserved for the landfill repository will be larger. It is also assumed that the waste packages can be placed in contact with each other.

Table 9-1. Dimensioning calculations for different waste masses.

Dimensioning calculations		Case 1	Case 2	Case 3	Case 4	Note
Amount of mass deposited	**t**	32613	40000	50000	60000	
Number of containers required		1165	1429	1786	2143	
Width of the waste filled area	**m**	60	60	60	60	
Number of containers in a row (short side, one layer)		24	24	24	24	Container width 2.438 m
Total height of waste packages	**m**	8	8	8	8	
Number of container layers		3	3	3	3	Container height 2.591 m
Number of containers in a row (short side, three layers)		72	72	72	72	
Number of container rows needed		16.2	19.8	24.8	29.8	
Rounded number of container rows		17,0	20,0	25,0	30,0	
Length of the waste filled area	**m**	103	121	151	182	Container length 6.058 m

Assuming that all waste would be deposited in 20´ open top ISO shipping containers (L 12 m, W 2.4 m and H 2.6 m), the dimensioning factor is the maximum bearing capacity of the containers (28 t), independent of the volume of the waste produced (see Table 9-2). This is because the containers have a volume capacity of 33 m^3, but loading capacity of only 28 t. In addition, the density of the waste is >> 1000 kg/m^3.

Table 9-2. The volume of deposited concrete and soil waste depending on the pre-treating option selected. However, considering packing in an ISO 20' shipping container, the dimensioning factor is the weight of the waste.

Masses	**m (t)**	**ρ(kg/m³)**	**V (m³)**	**Note**
Total mass of concrete	32413			
Normal concrete (95 w-%)	30792			
Heavy concrete (5 w-%)	1621			
Soil	200			
Total mass of waste deposited	**32613**			
Volumes (including different treatment options for concrete)				
Volume of soil	**m (t)**	**ρ(kg/m³)**	**V (m³)**	**Note**
Soil	200	1330	**150**	
Effective volume of concrete	**m (t)**	**ρ(kg/m³)**	**V (m³)**	**Note**
Effective volume of normal concrete	30792	2400	12830	
Effective volume of heavy concrete	1621	3700	438	
Total effective volume of concrete	32413	2443	**13268**	
Volume of crushed concrete	**m (t)**	**ρ(kg/m³)**	**V (m³)**	**Note**
Volume of normal crushed concrete	15396	1800	8553	Range 1800 - 2200 kg/m³
Volume of heavy crushed concrete	810	2500	324	Estimation 2500 kg/m³
Total volume of crushed concrete			**8878**	
Volume of cement stabilized crushed concrete	**m (t)**	**ρ(kg/m³)**	**V (m³)**	**Note**
Proportion of concrete (70 V-%)	16207	1221	13268	
Proportion of cement (30 V-%)	8188	1440	5686	
Total mass and volume of stabilized cement	24395		**18955**	
Density of the stabilized cement		1287		
Volume of concrete blocks	**m (t)**	**ρ(kg/m³)**	**V (m³)**	**Note**
Effective volume of concrete blocks			6634	
Volume of concrete blocks, void volume 5 %			6983	
Volume of concrete blocks, void volume 10 %			**7371**	
Volume of concrete blocks, void volume 20 %			8293	
Volume of concrete blocks, void volume 30 %			9477	
Amount of shipping containers needed				
Container (open top shipping container 20´)	**m (t)**	**ρ(kg/m³)**	**V (m³)**	**Note**
Outer volume			38	
Maximum capacity (inner volume)			33	
Maximum capacity (tonnes)	28			
Amount of containers needed	**m (t)**	**V (m³)**	**Amount**	
Total mass to be deposited	**32613**		**1165**	
Total volume of containers		**44572**		

Concept description, natural and engineered barriers

The concept description is based on the base case (Case 1 in Table 9-1) and is shown in Figure 9-1, Figure 9-2 and Figure 9-3. The structures presented in the cross-section can be divided into three main categories as described in Section 2.1.4.

In addition, there shall be separate drainage systems for controlling a) surface runoff water (inclination + ditches), b) water infiltrated through the topmost barrier layer (drainage layer) and c) leachate water.

The performance targets for different engineered barriers and examples of suitable barrier materials and dimensions are presented in Table 9-3. The direction of the barriers in this table are from bottom to top.

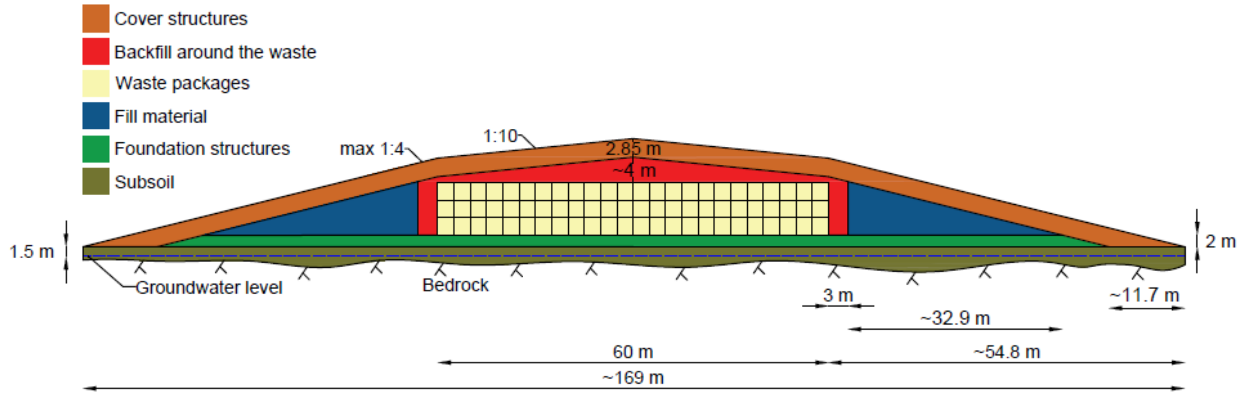

Figure 9-1. Cross-section of the landfill repository.

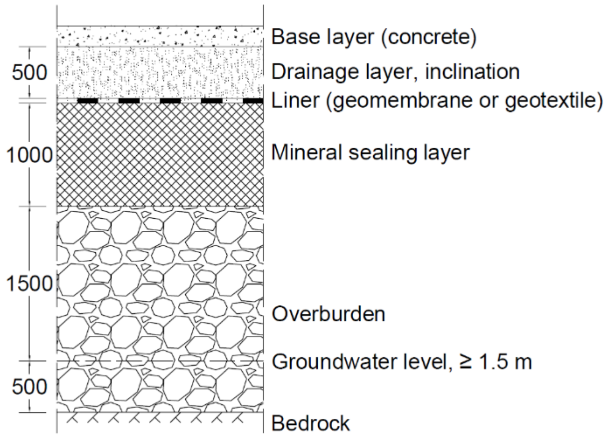

Figure 9-2. Cross-section of the foundation structures (see Table 9-2). Dimensions are in millimetres.

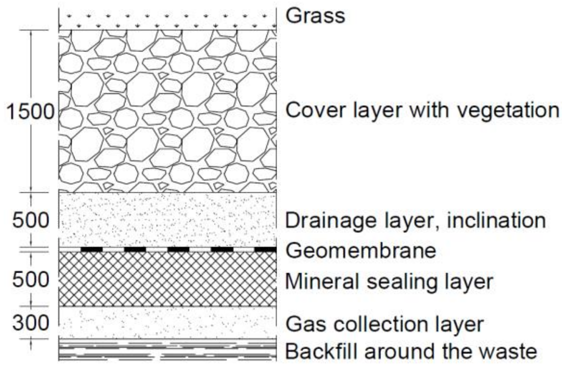

Figure 9-3. Cross-section of the cover structures (see Table 9-2). Dimensions are in millimetres.

Table 9-3. Barriers considered in the landfill repository from bottom to upwards.

Foundation structures	**Performance target/targets**	**Design specification**	**Reasoning**	**Material options**
Underlying sediment/soil & bedrock (natural geological barrier materials)	Limit dispersion of radionuclides. Provide sufficient stability and resistance for deformations.	Thickness ≥ 5 m and k-value < 1×10^{-9} m/s OR artificial barrier >0.5 m (< 1×10^{-10} m/s) Settlements should not jeopardize the performance targets of the different barriers.	Norwegian Waste Act (Act of June 2004 No. 930, section 9) defines that the base of a landfill shall have k-value 1×10^{-9} m/s and thickness of 5 m for hazardous waste landfills and 1 m for non-hazardous waste landfills.	Site specific. Vertical cut-off walls to be considered based on characteristics of the geological barrier and hydraulic connections to the surrounding environment.
Mineral sealing layer (artificial barrier layer)	Limit dispersion of radionuclides. Provide sufficient stability and resistance for deformations.	k-value < 1×10^{-10} m/s (measured in laboratory), thickness >0.5 m (recommendation for the considered site conditions for the conceptual design 1 m).	Norwegian Waste Act (Act of June 2004 No. 930, section 9, Appendix 1) defines that the geological barrier should be no less than 0.5 metres thick. k-value < 1×10^{-10} m/s recommended based on the fact, that at site the k-value is always somewhat higher at site than in laboratory.	Mixture of bentonite and aggregate (e.g. 6-10% bentonite). Cement-bentonite interaction considered, high-grade natural non-activated Ca-bentonite from Milos (Greece) as alternative for Na-bentonites.
Sealing geomembrane with filter layers	Limit dispersion of radionuclides	K-value < 1×10^{-11} m/s, but often local imperfections (holes etc.). Thickness is few centimetre depending on the selected sealing membrane. Requires a thin filter layers above and below to reduce the risk of breakage at installation.	Norwegian Waste Act (Act of June 2004 No. 930, section 9, Appendix 1, section 3.3): "…*a minimum thickness of 0.5 m shall be set up in addition to the geological barrier*"	HDPE-membrane or bentonite mat.

Drainage layer + system	Collection of leachate water (with contaminants).	>0.5 m (inclination ≥2%, k >1 x 10^{-3} m/s).	See above + Norwegian Waste Act (Act of June 2004 No. 930, section 9, appendix 1)." *c) collect contaminated water and leachate,* *d) treat contaminated water and leachate collected from the landfill if it is necessary to achieve the required discharge quality."* No specific guidelines given for the inclination or k-value. Recommendations for the inclination and k-value based on Finnish guidelines (SYKE 2008).	For example crushed rock or glacial gravel (6-32 mm). Drainage system consists of inclination and collection drains (concrete slab case) and pipes that lead to a leachate water inspection well/sedimentation pool. Inspection well or sedimentation pool shall be designed to limit radionuclide dispersion to the surrounding bedrock.
Base layer for the waste/waste packages	Provide sufficient bearing capacity, stability and prevent uneven settlements. Collection and control of leachate waters. Non-susceptible to ground frost	Sufficient bearing capacity (to be dimensioned in later design phases). Inclination of the layer 2% to direct the leachate waters in a controlled manner into the drainage system.		Concrete slab with drainage systems placed at the low most side of the slab. Concrete slab option requires some filter material between concrete/drainage layer. Filter cloths installed between different layers and sand cushion under the concrete slab.
Backfill around the waste	**Performance target/targets**	**Design specification**	**Reasoning**	**Material options**
Backfill material between/around waste packages	Drainage material, provide some sorption capacity	Depends on the type of the waste deposited	Some material needed between/around waste packages to be able to install cover structures and to provide stability/decrease settlements in the cover structures.	Rock flour, crushed rock (e.g. 1-10 mm).

Cover structures	Performance target/targets	Design specification	Reasoning	Material options
Gas collection layer + pressure release valves/gas collection system. *Optional* depending on the gas generation rate of the waste.	Layer for collecting gas generated e.g. by the hazardous waste to prevent gas pressure build-up in the repository.	Ability to collect gas, thickness e.g. 0.3 m. Filter layers/liner to avoid mixing with materials below/above.	Norwegian Waste Act (Act of June 2004 No. 930, section 9), appendix 1, section 4, based on which gases generated shall be gathered.	Coarse material + filter material/liner + valves/pipes.
Mineral sealing layer	Limit infiltration of water into the waste fill	k-value < $1x10^{-10}$ m/s (measured in laboratory), thickness ≥ 0.5 m.	Norwegian Waste Act (Act of June 2004 No. 930, section 9), appendix 1." *a) control water from precipitations entering into the landfill body,* *b) prevent surface water and/or groundwater from entering into the landfilled waste*".	Mixture of bentonite and aggregate (e.g. 6-10% bentonite). Trisoplast (polymer-clay-sand mixture).
Sealing geomembrane with filter layers.	Limit infiltration of waste into the waste fill. Shall not compromise stability of the landfill and form a slip plane. Gas tightness	K-value < $1x10^{-11}$ m/s, but often local imperfections (holes etc.). Thickness is few centimetres depending on the selected sealing membrane. Requires a thin filter layers above and below to reduce the risk of breakage at installation. Maximum inclination for the layer dimensioned based on geomembrane specific friction angle (e.g. max 22.5%, 1:4).	See above + Norwegian Waste Act (Act of June 2004 No. 930, section 9, appendix 1, section *3.3): "On sites for hazardous waste and non-hazardous waste, an artificial sealing membrane and a drainage layer with a minimum thickness of 0.5 m shall be set up in addition to the geological barrier specified in point 3.2 so as to ensure that leachate accumulation at the base of the landfill is kept to a minimum.* *<u>Requirements can be set for a surface sealing if this is considered necessary to prevent leachate formation."</u>*	Geomembrane (e.g. HDPE) with coarse surface (profile) for higher friction angle. Filter layer, e.g. sand or filter membrane.

Drainage layer + filters	Limit the water infiltrated through the upper sealing material layer	>0.5 m (inclination ≥2%, k >1 x 10^{-3} m/s).	Not defined in the Waste act.	Crushed rock or glacial gravel (6-32 mm) Separate collection system (shall not be combined with the leachate water drainage system)
Cover layer with vegetation	Limit the waster infiltrated to the repository, shelter the layers below from roots, erosion and ground frost.	> 1.5 m (maximum ground frost depth 1.5 m). k-value ~$1x10^{-8}$ m/s Grass planted for erosion control. No trees allowed (roots can puncture liners). Max inclination 1:4 (14°). At top of the waste maximum inclination 1:10 (5.7°) to enable surface run-off, but to decrease the risk of slip offs.	Not defined in the Waste act.	Natural masses (e.g. glacial) till or graded crushed rock with grain size distribution close to the Fueller curve.

In the design of the repository structures, desired functions and fulfilment of the long-term safety perspectives should be examined using specific analyses. Table 9-4 lists properties and analyses of different layers in a typical landfill that should be taken into account in the design and construction of these layers. In a landfill type of repository, similar analyses should be done. These geotechnical analyses should cover all phases of the repository implementation, including pre-operational period, operational period, and post-operational period. The analysis methods should be chosen by the designers of the repository and the designers are also responsible for carrying out the detailed and final analyses.

Table 9-4. Properties of the different layers to be taken into account during the design (modified from Wahlström et al. 2004).

	Foundation structures				Cover structures			
Properties and analyses to consider in the design	Subsoil	Mineral sealing layer	Drainage layer	Waste fill	Gas collection layer	Mineral sealing layer	Drainage layer	Cover layer
Stability	X	X	X	X	X	X	X	X
Deformations	X	X		X		X		
Bearing capacity	X	X		X	X	X		
Frost protection		X				X	X	
Preventing drying		X				X		
Erosion protection								X
Water permeability	X	X				X		
Hydraulic conductivity			X		X		X	

As an example, stability analysis should be carried out, not only for the subsoil but also for the waste embankment and cover structures. The stability analyses can be done using traditional slope stability analysis methods, and they determine the maximum inclination that can be used in the waste embankment and the cover structures. Other factors affecting the stability of embankment are filling height of the embankment and bearing capacity of the subsoil and foundation structures. In the analyses, care should be taken with the effects of geomembranes that are potential sliding surfaces.

Landfill type repository structures are demanding structures and design as well as construction require experience about the proper analysis methods and the material properties. During construction, experiences are required about the materials and proper working methods. All these should be included in the quality control (QC) and quality assurance (QA) programmes which should define the required material properties and working methods as well as methods to test the quality of the work. In general, QC and QA processes should be applied all through the production process, as well as Norwegian regulations, instructions and good practices ensuring operational safety.

9.1.2 Systems

Preliminary list of systems needed for the landfill repository are listed in Table 9-5.

Table 9-5. Preliminary list of systems needed for the landfill repository.

Systems
Clearance system / facility for the waste clearance with equipment and handling systems (outside the scope of this report)
Temporary storage area for waste packages
Transfer systems for transfer and installation of waste packages, see Section 9.2.2
Monitoring systems, see Section 9.2.8
Drainage system/systems
System for collecting and handling leachate water
Storage of raw materials for the landfill repository: temporary piling area, silos for different aggregate fractions.
Systems for handling and manufacturing barrier materials, e.g. sieves, silos and transfer systems for raw materials, see Section 9.1.7: Landfill repository production
Systems for installing barrier materials, e.g. systems for unloading the materials to the site, compaction rollers and plates, see Section 9.1.7: Landfill repository production.
Systems for quality control, inspection of installed masses, inspection of density of the installed layers etc. see Section 9.1.7: Landfill repository production
Documentation system (e.g. based on blockchains)

9.1.3 Safety classification

The classification of radioactive waste is defined in IAEA safety standard General Safety Guide GSG No. 1 (IAEA 2009). Since all the waste deposited in the landfill repository is cleared waste and is not considered as radioactive waste, it belongs to the IAEA safety class (IAEA 2009): *Exempt waste* (EW) meaning “waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purpose.” According to IAEA (2004), “Exempt waste contains such small concentrations of radionuclides that it does not require provisions for radiation protection, irrespective of whether the waste is disposed of in conventional landfills or recycled. Such material can be cleared from regulatory control and does not require any further consideration from a regulatory control perspective.” This means that the landfill repository and any of its barriers and systems have *no importance with respect to nuclear safety*.

9.1.4 Fire safety

When the waste has been emplaced, the cover structure is expected to shelter the waste from ground fire etc. However, there is small risk of fire of the organic liner material, if there is a defect in the cover structure. The risk of fire or explosion in a deposited waste container shall be evaluated based on the waste deposited (e.g. hazardous waste streams, generation of gas). The risk mitigation includes alternatives such as waste solidification and filling the void space of the container with a non-flammable material. See also, monitoring in Section 9.2.8.

9.1.5 Landfill repository adaptation for different waste volumes

The repository design can be adapted to different waste volumes by adding the amount of waste packages in a row and amount of row. However, the limiting factor may be the surface area reserved for the landfill repository.

9.1.6 Landfill repository construction in phases

In the base case (case 1), all waste packages are planned to be deposited at the same time. The construction of the foundation structure, deposition of waste packages and construction of the cover structure should be done during dry and frost free period, preferably during the spring/early summers with lower relatively air humidity in comparison to late summer and autumn. This is because, the construction and compaction of different barrier layers require stable conditions, so that for example the water content of the compacted layer does not increase above the specified optimum water content (defined with Proctor compaction tests).

If the storage space for the containers is limited, the construction and deposition can be done for example in three phases. If the foundation structure is built only in one phase and waste emplaced in phases (winter in between), care shall be taken on that the foundation structure is designed with protection against ground frost (e.g. in design of the concrete slab and insulation between the slab and the ground).

9.1.7 Landfill repository production

Landfill repository construction should follow the quality control (QC) and quality assurance (QA) programmes. The overall quality is secured by requiring proper quality for each part of the structure. The QC and QA programmes should contain the instructions of the materials and working methods to be used during the construction process. The quality of the work is tested throughout the construction process by testing the materials as well as constructed layers and other structures using adequate testing methods that are defined in the QC and QA programmes where numerical requirements should be set. During the construction process, height levels and locations of the structures need to be checked constantly.

Before construction, material to be used in each layer of the structure should be tested so that they would correspond to the design. The required tests depend on the performance targets and design specifications set for the structure layer where the material is going to be used. As an example, correct grain size distribution of the materials is crucial for the correct function of mineral sealing layer, drainage layer, and gas collection layer. For the mineral sealing layer, also at least the material composition (proportion of water, clay etc.), density, and hydraulic conductivity should be tested. In general, for all the soil layers, including mineral sealing layer, drainage layer, gas collection layer, protective layer for the membrane, and cover layer, the required properties should be tested before, during, and after their construction for their quality control. When testing the properties from the already constructed layers, it should taken into account that the layers are not disturbed. Properties and function of the membranes should be tested before and after their installation.

During the construction process, it is important to measure the height level of surfaces before and after construction of each layer to check that the layers fulfil their target thicknesses and inclinations. Proper compaction of the layers is also required during the construction process. Settlements of the subsoil and the constructed layers should be monitored during the construction process. Before starting to construct the cover layers, it needs to be secured that no more detrimental settlements will occur in the subsoil, foundation structures and waste fill layer (see Section 9.2.8 Monitoring). After construction of the cover layers, monitoring of the settlements should continue. Differences in the magnitudes of settlements can cause tensile stresses which can be detrimental for the mineral sealing layer in the cover structures. Settlements can also lead to disturbances in the drainage layer inclinations. Due to the possible settlements, the construction should be done in phases and with monitoring of the settlements; it is possible to estimate when each layer has settled, and it is possible to start constructing the next layer. Settlements can be monitored using for example settlement plates, levelling, or geophysical methods.

The most important thing to take into account during the construction is work safety. National regulations set for a safe working environment and working methods should be followed during the entire construction process. Accepted working methods including the safety principles should be included in the QC and QA programmes.

The prevailing weather conditions have a crucial effect on the construction of the structure layers of the repository. As already mentioned in Section 9.1.6, all the construction work is preferred to be done during dry and frost-free (preferable > + 5°C) period. The cover structures should also be constructed during spring so that all the necessary after work can be completed before the winter. If the cover structures are not constructed before the winter, the mineral sealing layer should be protected from freezing by some other methods. Materials of the mineral sealing layer are sensitive to weather as are also the geomembranes which should not be installed in winter conditions. Welding of the membrane joints is difficult also during rainy conditions and installation of the geomembranes is difficult during very windy conditions.

Preparation of the subsoil includes levelling of the surface to the desired height levels, taking into account drainage and stability aspects. Bearing capacity tests (plate loading tests) need to be carried out before constructing the mineral sealing layer.

Construction of the mineral sealing layer starts with testing the material properties to check its compliance to be used in the layer. First phase of the actual construction process should be a compacted test layer. This test layer is used for checking that the used methods and equipment are proper for fulfilling the desired targets set for the layer. From the test layer, it is desired to test its desired properties, including grain size distribution, water content, density, hydraulic conductivity, evenness and height level (thickness) of the surface, and bearing capacity (a plate loading test). If the desired targets are achieved with the used methods, construction of the actual mineral sealing layer can be carried out, but the aforementioned properties should be tested also during the construction work of the mineral sealing layer. Proper compaction of the mineral sealing layer is crucial due its effects on the hydraulic conductivity and bearing capacity of the layer. The compaction should be done in maximum of 500 mm layers. It is important to protect the constructed mineral sealing layer from possible freezing and also from erosion, drying, and wetting.

As it is done for the soil materials that are used in the different layers of the repository, also the geosynthetic products (geomembranes etc.) should be tested before they are installed. As for the soil materials, tests for the geosynthetic products should be performed using standards. Properties to be tested include for example thickness of the membrane, hydraulic conductivity, and tensile strength. The membranes should be installed only on even and smooth surfaces that has no large or sharp-edged rocks that could damage the membranes. Inclination of the surface should also be checked before the installation. The membranes are heavy and not easily handled. Thus, proper equipment for the installation is needed. One possibility is to use a digging machine with required auxiliary parts. Joints of the different membranes need to be connected using for example welding. Tightness of the welded joints should then be tested. After the installation it is recommended that the membranes are covered to protect them from any damage and also from UV radiation and thermal stresses. It is not allowed to drive with vehicles on the membranes before there is thick enough layer of soil material on the membranes. Between the membranes and other barrier layers, a thin protective layer should be constructed or a protective fabric or geotextile should be installed to protect the membranes from mechanical damages.

The drainage layers and the gas collection layer are constructed to their desired thicknesses and inclinations. As for the other soil barrier layers, the materials should be tested before the construction and testing of the installed layer should be performed during and after construction of the layers. Construction of the drainage layers and gas collection layer includes installations of pipe systems with wells. Desired height levels as well as inclinations of the pipe systems are crucial for the function of the layers.

The cover layer is usually constructed in two phases where the upper part of the cover layer is constructed for vegetation. As it was mentioned, it is important to construct the cover layer on top of the mineral sealing layer before the winter when the ground frost starts to occur. It is important that the thickness of the cover layer is not reduced from the design so that the thickness is adequate for the frost protection and one of the design criteria for the upper layer is that it should ensure that the mineral layer does not freeze. Inclinations of the cover layer surface should also follow the design. Too small inclination is not leading the water away from the surface effectively enough whereas too high inclination can lead to stability problems. The vegetation layer is constructed based on the erosion control and landscaping plans.

9.1.8 Examples of existing landfill repository sites

One example of a near surface repository based on a landfill-type of a design from Ringhals, Sweden is presented in Figure 9-4. Landfill type of repositories are constructed above the groundwater table. The foundation structures built depend on the local geological conditions, for example the bearing capacity, stability, permeability and thickness of the sediment layer. The overall structure of a landfill type of a repository and the engineered barriers used are in general similar to those of landfills for normal or hazardous waste (Keto et al. 2019).

The Ringhals near surface facility is a repository for VLLW including radioactive waste such as 1) combustible operational waste (trash, cloth and plastic) that is compacted into pallets; 2) non-combustible waste (mainly metallic waste); and, 3) resins (Aronsson 2019). The waste with the highest activity levels is packed in metal containers (20' open top shipping containers with lids) is placed in the middle of the repository. The lower level waste is packed in plastic and placed around the metal containers. Free space inside the containers and between/around the containers is filled with rock flour. The repository was built in four campaigns (1993-2016) with own licences for each phases allowing deposition of a total 100 GBq of gamma radiation emitting nuclides, maximum concentration of 300 kBq/kg (or nuclide specific) and maximum surface dose rate of 0.5 mSv/h (Aronsson 2019). The repository was built on exposed bedrock surface and was evened out the with concrete. Overlying the concrete there was a drainage layer made of coarse crushed rock. Above the waste, the layers preventing infiltration of precipitation to the repository consist of a bentonite mat and moraine (glacial till). The inclination of the top layers is 1:3 (Aronsson 2019).

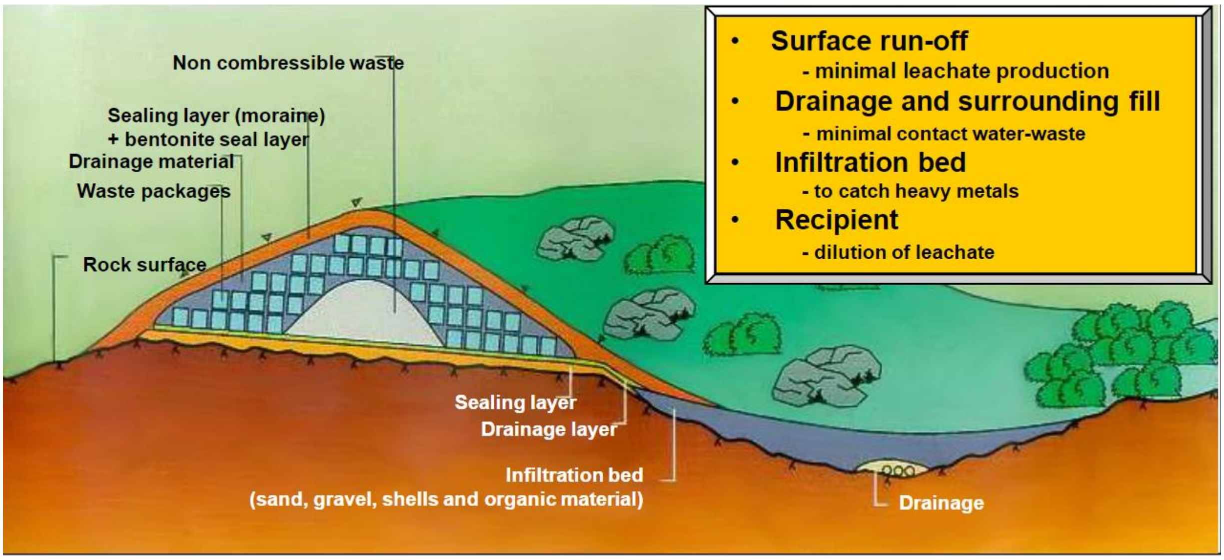

Figure 9-4. Conceptual illustration of a landfill type repository located in Ringhals, Sweden (Aronsson 2019).

A similar type of a landfill repository for VLLW is located in Forsmark, Sweden. This is located on a layer of sediments (glacial till) and fill material (Vattenfall 2008, Keto et al. 2019). The design of the repository is combining regulations for normal and hazardous waste landfills, based on which the underlying geological barrier shall have hydraulic conductivity < $1x10^{-9}$ m/s and minimum thickness of 1 m for normal waste and 5 m for hazardous waste. The Norwegian Waste Act (avfallsforskriften), chapter 9 sets the same requirements. In addition, the infiltration of the overlying and underlying hydraulic sealing layers shall not exceed 50 L/m^2/a for normal waste and 5 L/m^2/a for hazardous waste. According to Vattenfall (2008), the infiltration of the precipitation/surface runoff waters to the waste have been limited to ~1 L/m^2/a (hydraulic conductivity ~$1x10^{-11}$ m/s) with a combination of the structure overlying the waste consisting of a bentonite mat and a layer consisting of mixture of bentonite (5 wt.%) and rock flour. The sealing layer below the waste has a thickness of 0.4 m and is comprised of bentonite (1 wt.%) and rock flour. The glacial till layer beneath the sealing layer has a thickness of ~2 metres and hydraulic conductivity of ~$1x10^{-8}$ m/s. The voids between the waste packages are filled with rock flour and the drainage layers consist of coarse crushed rock (Vattenfall 2008).

9.2 Operation

9.2.1 Activities and schedule

List of activities linked to the life-span of the repository is presented in Table 9-6. The activities are according to IAEA recommendations (IAEA 2017). In addition, some case specific actions have been added to this list and marked with asterisk (*).

Table 9-6. Preliminary list of activities and schedule in pre-operational, operational and post-closure period.

Period	**Activity**	**Preliminary time-schedule**
Pre-operational period	Decision for action	2020
	Development of disposal concept of the landfill repository: - Concept description - 2-3 design iteration rounds based on a) input from stakeholders and authorities, b) development in Norwegian regulations and guidelines concerning disposal of radioactive and cleared radioactive waste, c) more detailed waste inventory data and d) expert judgement (review by third party). - Final detailed facility design few years prior to operations to have time to prepare for the operations and building up of the facility for production of the repository.	Concept description 2020, Design iterations ~10 years. Applying of construction and operation licence 2-5 years before start or construction.
	Safety strategy	Along with the development of the conceptual design
	Site investigations and environmental impact assessment including for example studies on: - Geographical, geological, hydro(geo)logical conditions. - Evaluation of the local risk for earthquakes and landslides. - Drilling investigations and soil samples to study the characteristics and thickness of the sediment layer, location of the groundwater table, flow directions of the groundwater and quality of the groundwater. - Geophysical studies, e.g. seismic methods (in addition to drilling) to study the thickness and characteristics of the sediment layer and underlying bedrock (e.g. location of fractures and faults). - Studies on surface hydrology (surface water runoff directions). - Baseline studies (e.g. background radiation, vegetation etc.).	For applying the construction/operation licence
	Site selection - Will be done based on the local site investigations at the Norwegian national repository and environmental impact assessment.	For applying the construction/operation licence?
	Facility designs: - Waste clearance facility + storage (outside the scope of this project).	-For applying the construction/operation licence

	- Production facility and temporary storages for the repository	
	Development plans for R&D and monitoring	For applying the construction/operation licence
	Detailed plan for decommissioning needed as an input for the landfill repository including methods and characteristics of the waste streams.*	For applying the construction/operation licence
	Detailed waste inventory data including hazardous waste streams and waste characteristics (taking into account pre-disposal)*	For applying the construction/operation licence
	Waste clearance, packing and storage. All waste assumed to be cleared by start of the operations.*	Prior to start of the operational period
Operational period	Approval for starting construction/operations.	Start of operations either in one or in several campaigns. Campaigns during dry period. Duration of a campaign: 2-6 weeks. Total duration 1-3 years depending on the number of campaigns.
	Preparations at the site	
	Construction of the landfill repository foundation layers and drainage systems	
	Emplacement of waste packages and backfill material	
	Construction of the cover structure (closure of the repository) and drainage systems	
Post-closure period	Active monitoring, periodical monitoring possible also after that as institutional control	Active maintenance until National Facility closure.
	Active maintenance e.g. of the cover structure if defects found.	Active maintenance until National Facility closure.
	Passive measures: e.g. restrictions for land use for farming etc.	Over hundred years

9.2.2 Transfer and installation of waste packages

When the waste packages are transferred from the storage to the site, the transfer can be done with trucks (loaded with a sideloader integrated into the truck or loaders at the storage site and at the repository site). If the storage is located close to the site, the transfer and also installation could be performed with heavy duty telehandlers (e.g. Manitou MHT-14350 with maximum loading capacity of 35 t, maximum lifting height of 13.6 m and maximum reach of 8.5 m, see Figure 9-5. Another alternative for installation (bot not for transfer) is a mobile crane, with better reaching in comparison to a telehandler and lifting capacity from 35 up to 50 t.

Figure 9-5. Example of a telehandler that can be used for handling the waste packages. Figure by Manitou: https://www.manitou.com/en/p/VOdgtioAACwAKvsQ.

9.2.3 Emplacement of backfill around the waste packages

The emplacement of barrier materials is described in the section "Landfill repository production" (9.1.7).

9.2.4 Controlled and uncontrolled areas

From a radiological safety perspective, all areas pertaining to the near surface facility can be classified as uncontrolled, since only decommissioning waste with activity concentrations below clearance levels and non-radioactive hazardous waste are considered for disposal. Nevertheless, access controls to the site will be in place throughout the operations and in the post-closure phase as part of institutional control. The waste arriving at the near surface disposal facility will be checked for surface dose rate and contamination. Note that the area of the landfill repository will be part of a bigger complex with decommissioning and other waste disposal activities that require attention from the viewpoint of radiological safety.

9.2.5 Radiation protection

Since the near surface disposal facility can be classified as an uncontrolled area as a whole from radiation safety perspective, monitoring of individual's radiation exposure (e.g., personal dosimeters) is not mandatory. However, part of the monitoring programme aims at the control of radioactive releases in liquid form and airborne in the form of gases or dust.

9.2.6 Incidents and accidents

Since the waste deposited will be non-radioactive, incidents and accidents concerning nuclear safety do not have to be considered for the landfill repository. However, risks concerning occupational safety and environmental issues (e.g. leakage of hazardous waste from the waste packages) should be evaluated according the regulations given in the Norwegian regulation. All operations shall be performed taking into account Norwegian legislation concerning operational safety in landfill building sites and the adjoining nuclear facility.

9.2.7 Safeguards

Not applicable since only decommissioning waste with activity concentrations below clearance levels and non-radioactive hazardous waste are considered for the near surface disposal facility.

9.2.8 Monitoring

In the context of the safety of a near surface disposal facility, monitoring means the continuous or periodic observation and measurement of radiological, environmental, engineering and other relevant parameters. The monitoring system should be planned and implemented already at a very early stage of repository development taking into consideration the long-time period and the demanding site-specific environmental conditions in terms of meteorology and presence of hazardous substances. Monitoring results can be used to demonstrate compliance with regulatory requirements during the licensing process and oversight. In particular, the monitoring programme should be coordinated together with the needs of the required safety and environmental impact assessments (IAEA 2014). In addition, monitoring can enhance the confidence of stakeholders, eventually leading to increased public acceptance. However, as highlighted earlier (Section 2.1.4), the long-term safety of the disposal facility needs to be ensured passively and active measures such as monitoring can only be supportive to the passive safety approach (IAEA 2002).

The following discussion serves only as first orientation for possible monitoring activities. The monitoring programme will be developed in accordance with the Norwegian Waste Act (Act of June 2004 No. 930, section 9, Appendix 3 ("Vedlegg III. Kontroll- og overvåkingsprosedyrer i drifts- og etterdriftsfasen") and should be made subject to audit and independent verification by the regulatory body (IAEA, 2014). The monitoring parameters and measurement locations and frequencies need to reflect the site-specific conditions and waste characteristics and will be specified in the licensing documents, together with threshold values triggering mitigation actions for normal, incident and accident conditions.

The purpose and extent of monitoring activities differ between the different phases of repository development (i.e. pre-operational, operational and post-closure phase). For the site investigation and selection, any existing environmental data from previous monitoring activities should be taken into account, which is especially relevant for the facility design and planning of the operations with regard to extreme weather conditions (e.g., wind, snow/ice loads, flooding). After a site has been selected, a baseline survey will be conducted at at least three locations (Norwegian Waste Act (Act of June 2004 No. 930, section 9, Appendix 3) serving as yardstick for the comparison with future monitoring results to, e.g. evaluate the impact of the construction and operation of the facility (IAEA, 2014). For example, the following aspects can be included in the monitoring programme (IAEA, 2002):

1. Meteorological conditions: precipitation, temperature, wind, evaporation.
2. Geomorphological aspects: erosion mechanisms and their rates.
3. Hydrological conditions: runoff, flow characteristics of existing water streams, lakes and wetlands.
4. Hydrogeological conditions: infiltration and evapotranspiration, permanent and temporary springs, depth and oscillation of the water table, preferential flow pathways, direction and rate of groundwater flow in both vadose and saturated zones, travel times to existing and potential outflow and extraction points.
5. Geochemical conditions and environmental quality: water quality, concentrations of naturally occurring radionuclides in a variety of environmental media, retention of radionuclides by soil and geological materials.
6. Radiation background level.
7. Flora and fauna

Note that monitoring of both surface water and groundwater must be carried out up- and downstream of the disposal facility. During the operational phase, the monitoring objectives additionally include the physical health of workers and the detections of deviations from the expected conditions. The monitoring programme can include:

1. Occupation of the individual disposal cells of the repository and the remaining capacity.
2. Condition of the waste packages: integrity, control of surface dose rate and contamination of waste packages.
3. Integrity and functionality of the engineered (and/or natural) barriers. In particular, settlements of the foundation layer need to be monitored to ensure the functionality of drainage and sealing layers and backfill structures. The monitoring of settlements should expand to the cover structures after their construction.
4. Radioactive releases in liquid form and airborne in the form of gases or dust.
5. Leakage waters from drains: flow rate and location of the leakage, chemical composition of the leakage water, including radioactive isotopes.
6. Leakage of gasses.
7. Perimeter protection and access control

Post-closure monitoring data can be used to validate models applied in the safety evaluations of the facility. Monitoring in the post-closure phase may also indicate system malfunctions or a deterioration of the barrier performance, so that corrective measures can be taken (IAEA 2003a). However, no overly extensive reliance can be placed upon them with regard to post-closure safety. In addition to the monitoring activities during the planning, construction and operation of the disposal facility (Section 9.2.8), post closure monitoring can include (IAEA, 2001):

1. Soil moisture content in the cover structures and water composition.
2. Vegetation growth and evapotranspiration.
3. Biological intrusion.
4. Infiltration into disposal units.
5. Seepage through cut-off walls (if part of the barrier system).
6. Visual observations: erosion, cracking and deformations, condition of the drainage ditches etc.

It is important to bear in mind that the selection and installation of monitoring systems may not deteriorate the barrier performance by, for example, creating preferential pathways for water flow and contaminant transport (IAEA 2001b). In accordance with the monitoring strategy to be developed before closure, monitoring activities in their extent and in terms of the frequency of measurements are anticipated to decrease over time. An essential precursor to the discontinuation of institutional controls is the compliance of monitoring results with the imposed (regulatory) requirements for an extended period of time (IAEA 2003a).

9.3 Decommissioning and closure

9.3.1 Activities during the closure period

The closure needs to be considered already in the initial design of the repository and a plan for the closure of the near surface disposal facility needs to be developed at an early stage, constantly updated in an iterative manner and subject to quality assurance (QA) (IAEA, 2001). In general, the closure plan takes into account (IAEA 2001b, 2014):

1. Site characteristics (e.g., topography, precipitation and geology and hydrogeology);
2. Waste characteristics in terms of inventory, waste form and packaging;
3. Time and location of waste emplacement;
4. Types of intended barriers, e.g., backfill or final cap. This includes the used materials, installation techniques and a description of the expected barrier performance;
5. The mode of waste emplacement, i.e. the disposal of the waste in one or in several campaigns. The closure of parts of the disposal facility should be undertaken early after the waste emplacement is completed. The possible temporal covering of individual disposal cells and the timing of the final closure need to be considered in the evaluation of the post-closure safety;
6. Monitoring and surveillance of the facility during the closure period;
7. Possible deviations from the planned activities during operation and closure of the facility;
8. Decommissioning of no longer needed parts of the facility (e.g., administrative buildings, temporary storage units, etc.) and environmental restoration;
9. Transfer to institutional control including the type and duration of planned actions.

Main tasks during the closure period include the placement of engineered barrier system such as backfill, geo-membranes and drainage systems (see Section 9.1.1 for details) and monitoring systems (Section 9.2.8).

9.3.2 Decommissioning

When the operations at the site cease, any auxiliary buildings and structures (e.g., facilities for temporary storage, conditioning and packaging of waste, interim cover structures protecting open disposal cells from infiltration) need to be dismantled. Since the activity concentrations of the waste foreseen for the facility are below clearance limits, special provisions for radiological contamination are not required. Special attention is required for drainage systems beneath the facility if designed to be functional only during the operational phase. When these systems are to be removed during the closure phase, the created voids need to be filled and the impact on the overall stability of the completed facility needs to be taken into account. If it is envisaged to dispose of the waste arising during the dismantling phase also in the near surface capacity, its capacity needs to be designed accordingly (IAEA 2001).

10 SUMMARY

The concept description for a Norwegian National Facility for nuclear waste is described in this report. The facility is designed to act as a final repository for all nuclear waste generated so far and the waste that will be generated in Norway over the next 100 years after its commissioning. The decommissioning waste from the research reactors in Halden and Kjeller makes up the majority of the waste volume. The report describes the first concept description, as of 2020.

The concept description for the National Facility contains the following repository types:

- Intermediate depth repository for very low, low and intermediate level waste,
- Deep geological repository (DGR) for high level waste,
- Deep borehole repository for high level waste as an alternative to the DGR,
- Landfill-type repository as an option for non-radioactive decommissioning waste, mainly soil and concrete.

The disposal facility concept description reported in this document acts as a basis for further design of facilities and production of alternative combinations for decision making on selecting the types of facilities for further studies. The final design will not necessarily include all the repository types mentioned above.

The deep geological repository design is based on the KBS-3 repository concept developed in Sweden and Finland. The underground repositories have been designed for operations taking place at two levels: very low, low and intermediate level waste repository at intermediate depth and the deep geological repository for high level waste either at the depth of 400 m or, in the deep borehole alternative, at the maximum depth of 3500 metres. The feasibility of borehole disposal is discussed because that concept is less mature than KBS-3.

The report contains descriptions on initial data and assumptions made regarding inventory and packaging, but these are not in the focus for this work. The basic scenario for fuel pre-disposal treatment is oxidation of metallic uranium to uranium oxide. Alternative scenarios that have also been considered for spent fuel treatment are no treatment at all and two options for reprocessing.

Activities related to planning, construction, operation, decommissioning and closure phases with regard to operational safety and radiation safety, safeguards of nuclear materials, required systems and operation as well as overall schedule are briefly described. Site selection and related activities and a preliminary design for the required buildings and facilities above ground are also described.

The concept description described in this report maintains maximum flexibility to allow changes in the design solutions. Waste acceptance criteria or other details are not locked down at this stage. The concept description given in this report will be used for preliminary costing and scheduling analysis in the next phase of the project.

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