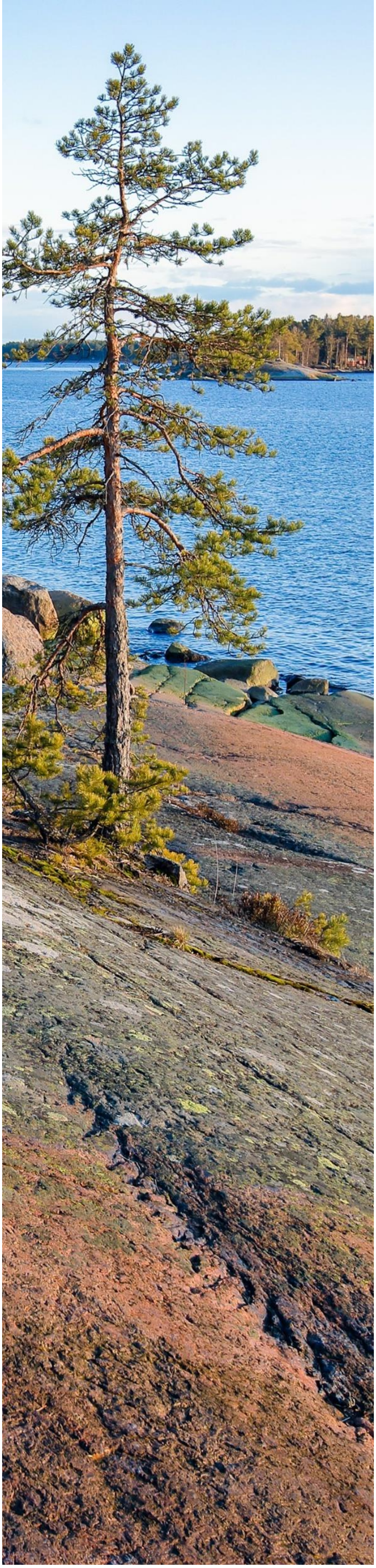

Technical Report

Deep Borehole Disposal Canister

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ABSTRACT

Norway's inventory of high-level radioactive waste originates from the research reactors in Halden and Kjeller, taken out of operation. NND is developing a comprehensive strategy for management of radioactive waste. For high-level waste, this includes two options: deep geological repository or deep borehole disposal.

This report provides basic information about the deep borehole disposal canister design. First, the safety functions of the canister in deep borehole disposal were described. The described canister safety functions are containment, radiation shielding, sub-criticality, limiting temperature, limiting corrosion and operability. Additionally, the processes that can affect the canister and its long-term safety were also described. Later, the safety functions and requirements for the canister were quantified.

The quantified safety requirements were subsequently used to design a canister for deep borehole disposal in Norway. A static strength assessment was used to calculate the necessary wall thickness for the canister. In addition, the manufacturing process of the canister was described, and conclusions for the canister design were made. For the canister design, a canister made out of corrosion-resistant steel, in this case austenitic steel grade, was chosen. The wall thickness is 80 mm, and the canister is closed by electron beam welding.

Furthermore, the geochemical environment and possible corrosion processes are described to predict the long-term performance of the canister. Also, possible interactions of the canisters with the borehole sealing system are described. The necessary working steps are described, including manufacturing and disposal. Also, there is a description of the technical properties of the encapsulation plant and transport cask. Additionally, the quality assurance during encapsulation is described. The report ends with conclusions and recommendations.

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1 INTRODUCTION

1.1 Background

Norwegian Nuclear Decommissioning (NND) is working 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 characterised by high-level waste (HLW) 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. NND is developing a comprehensive strategy for management of all classes of radioactive waste. Such a strategy could include the following facilities:

- Intermediate depth repository for low and intermediate level waste,
- Deep geological repository OR deep borehole repository for high-level waste,
- Landfill-type repository for non-radioactive decommissioning waste.

Repository types are presented in the report "Concept Description for Norwegian National Disposal Facility for Radioactive waste" (Ikonen, et al. 2020). The report includes concise concept descriptions of the possible disposal options. Borehole disposal concept was further developed in Fischer et al. (2020).

This report provides newly developed information for the deep borehole disposal canister and, therefore, further brings the concept to a more mature level.

1.2 Borehole disposal concept

Deep geological repositories use a combination of engineered and natural barriers to safely contain and isolate radioactive waste from people and the environment. Among the different geological formations considered suitable for hosting geological repositories, crystalline rocks are characterised by their high strength, thereby providing cavity stability, low heat sensitivity, low permeability and beneficial dissolution properties, see, e.g., BGE (2020), Hagros, et al., (2021) or Posiva-SKB, (2017).

The borehole disposal concept consists of drilling a borehole to a depth of several kilometres, emplacing waste canisters containing spent nuclear fuel (SNF) or HLW in the lower part of the borehole and then sealing the upper part of the borehole. The borehole can be designed completely vertical or with a certain deflection of the drilling line. Even a horizontal orientation within the disposal zone is possible but does not represent the currently favoured technical solution. Still, also other types of waste can be disposed of in boreholes, but the limited volume of the boreholes need to be kept in mind. Most of the borehole disposal concepts are based on the disposal of the waste packages in crystalline basement rock (typically granitic rock) (Chapmann, 2019).

Borehole disposal facilities consist of surface facilities, such as disposal hall structure and emplacement rig, and the drilled deep borehole directly under the rig.

Disposal of radioactive waste in deep boreholes has been examined as an alternative (or complementary solution) to mined geological repositories. Primarily for countries with limited radioactive waste, deep borehole disposal is particularly interesting. For larger waste volumes, numerous boreholes would be required. In these cases, mined repositories can have advantages over borehole disposal.

1.3 Borehole disposal concept for Norway

The deep borehole disposal concept for Norway is described in (Fischer, Engelhardt, & Wanne, 2020) and briefly summarised here. Due to the small amount of high-level waste in Norway, deep borehole disposal is a possible alternative to a mined repository. With this concept, deep boreholes are drilled into crystalline rocks from the surface of the Earth. After completion of waste disposal in the lower section, the upper section of the borehole is sealed with a long-term barrier system. The safety case for such a concept would place great emphasis on the great depth of burial, which shall ensure that the waste remains isolated from the accessible environment.

Crystalline rocks are widespread and offer advantageous conditions for deep borehole disposal in Norway. The geology of Norway is characterised by crystalline rocks sparsely covered with marine clay and other Quaternary deposits. A borehole would reach the hard rock at a shallow depth. The low geothermal heat flow and thus relatively low temperatures in the rock in Norway are also considered to be advantageous. In wide areas of Norway, seismicity is low. Also noteworthy is Norway's extraordinarily extensive expertise in deep drilling technology. There are numerous specialist companies and research and test centres that could contribute to the development of borehole disposal techniques. In addition, experience in drilling geothermal wells is constantly being gained in Norway.

The deep borehole repository is designed for the disposal of radioactive waste in deep geological formations. It consists of a single borehole in which the waste packages are disposed. For the concept description, the depth of the borehole was chosen to be 3500 metres, of which the lowest 500 metres are used for disposal of the waste packages. Seal and backfill zones are above the disposal section.

For the construction phase, a surface area of about 150x150 metres is required for the drilling equipment, the drilling rig itself and other supporting facilities. It also includes an area for transportation and material storage. Once the construction (drilling and casing of the borehole) is completed, the surface area is converted to disposal operation. The same surface space area is assumed for the disposal operations. After the disposal operation, all the equipment will be dismantled and the borehole sealed and plugged up to the surface.

After completion of all operational steps, the surface structures and buildings are dismantled and only long-term monitoring equipment will stay in place.

See Figure 1-1 for illustration of Norwegian National Facility with the deep borehole disposal option.

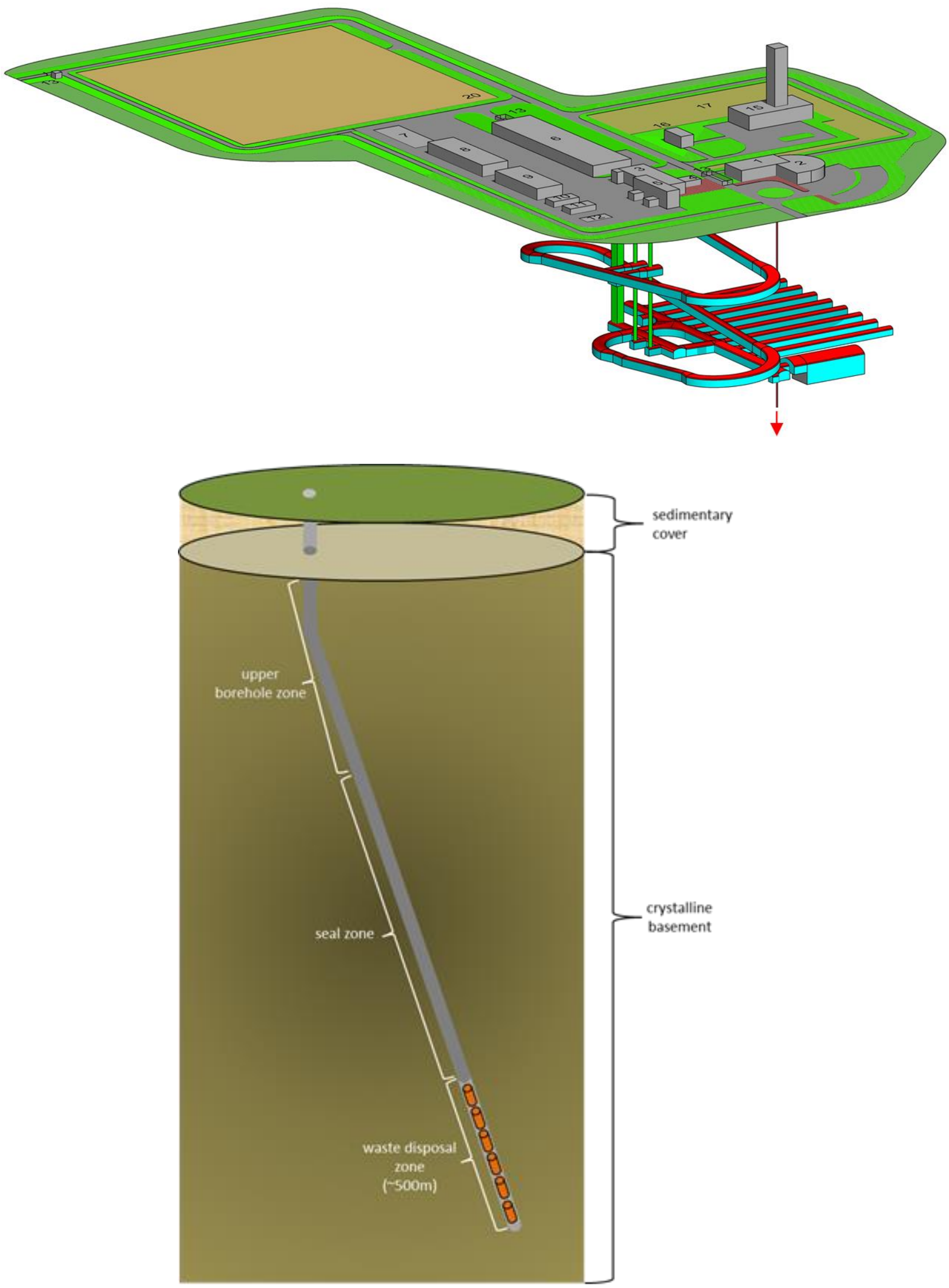

Figure 1-1: Illustration of the Norwegian National Facility (above) with surface and underground infrastructure with option of deep borehole for HLW disposal. The borehole is the thin black line below building 15, and it continues out of the figure with the red arrow. Below – schematic view of the borehole disposal, based on (Ikonen, et al., 2020) (Fischer, Engelhardt, & Wanne, 2020).

1.4 Scope of work and structure of the report

The aim of this report is to generate the first concept version of a deep borehole disposal canister for the disposal of high-level radioactive waste in Norway. Therefore, the report uses the following structure.

At first, there is the description of the safety functions of a canister in the borehole concept.

After that, the safety functions, such as the minimal post-closure lifetime, are quantified, and quantifications of the impacts and loads to the canister, identified from the known or assumed conditions, are used to design the disposal canister, including wall thickness and material. The dimensions of the canister are defined, e.g. by the planned borehole diameter, emplacement technique, length of fuel elements and in addition by the safety functions that have to be determined to achieve a suitable design.

Chemical impacts are especially relevant for long-term safety and stability. Thus, the work will include a description of the expected chemical environment and relevant corrosion mechanisms.

Subsequently, the emplacement of waste in the canister is described for a generic waste package. It is also described how the canister may be sealed. The sealing methods reflect the safety functions of the canister (pre- and post-closure) and operational safety during encapsulation.

The quantification of the safety function and the design of the canister allows a description of QA/QC methods of the canister and its relevant components. In addition, the description of QA/QC methods for the sealing of the canister during encapsulation and the finished canister are described.

The report finishes with the description of the working steps for canister production and encapsulation. A description of a potential transport/storage cask (“supercontainer”) for the filled borehole canisters to provide radiation shielding and mechanical protection of the canister during storage and transfer (within disposal site) to the borehole. Also, there is a description of the necessary technical requirements of an encapsulation plant.

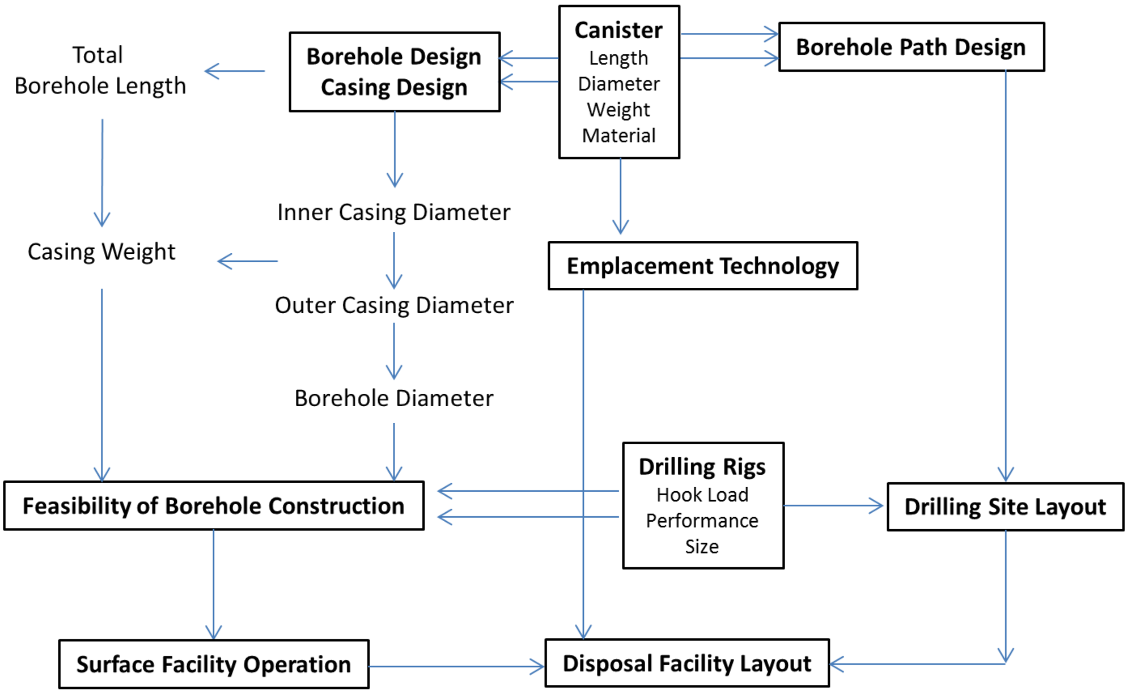

Figure 1-2: Planning scheme for a first design of a deep borehole disposal facility in Norway (Fischer, Engelhardt, & Wanne, 2020).

2 SAFETY FUNCTIONS FOR BOREHOLE DISPOSAL

2.1 Requirements for the deep borehole repository

(Hagros, et al., 2021) give a systematic approach to develop a generic requirements management system for the Norwegian National Facility. The work was intended to guide the further development of the disposal concepts and to support the overarching goal of developing a safety case for either a specific or a generic site.

(Hagros, et al., 2021) list safety requirements and technical requirements for the different repository types in the National Facility. The work relies on information available in Norwegian regulations (provided by NND), IAEA Safety Standards (including fundamental safety principles, GSR, SSR, GSG, and SSG) and relevant standards from ICRP and OECD-NEA. Safety function for Deep Borehole Disposal (DBD) in general or for DBD canisters can be determined from the documents. A major design requirement for DBD can be stated as follows.

"A disposal facility is designed to contain the radionuclides associated with the radioactive waste and to isolate them from the accessible biosphere. The disposal facility is also designed to retard the dispersion of radionuclides in the geosphere and biosphere and to provide isolation of the waste from aggressive phenomena that could degrade the integrity of the facility. The various elements of the disposal system, including physical components and control procedures, contribute to performing safety functions in different ways over different timescales." (SSR-5 (IAEA 2011))

An important design principle to provide containment, isolation and retardation is the use of a multi-barrier system, consisting of the host rock together with the engineered barrier system (EBS). The canister is one part of such an EBS. All structures of the EBS provide specific safety functions:

"The physical elements and their safety functions can be complementary and can work in combination. The performance of a disposal system is thus dependent on different physical elements and on other elements that perform safety functions, which act over different time periods. For example, the roles of the waste package and the host geological formation for a geological disposal facility may vary in different time periods." SSR-5 (IAEA 2011)

(Bollingerfehr, et al., 2020) developed a method for determining the safety functions of a canister. The requirements and the functions for repository canisters were derived using a top-down approach. In a first step, the currently relevant national and international laws and regulations were taken as a basis. From these, generic, i.e. abstract or general, canister requirements were developed for the respective phases of use of the canisters in the repository derived from the regulatory requirements. As a result, use- or phase-dependent generic cask requirements were formulated. The cask functions necessary to fulfil the phase-dependent requirements can be derived from these.

In the second step of the top-down approach, generic repository systems and associated safety and verification concepts were included in the considerations. The focus of the project was on the German HLW/SNF repository and included the three host rocks salt, claystone and crystalline formations. In this way, both the canister functions for fulfilling the requirements and the impacts for the respective host rock can be specified more concretely. In the further course, specific canister concepts for the individual host rocks can be developed on the basis of the generic canister concepts.

Finally, in the third and last step of the top-down approach, the repository site determined in the site selection procedure is considered with its specific properties and characteristics. Based on (i) the specific safety and verification concept to be developed for this site, (ii) the quantified site-related impacts, and (iii) the necessary canister functions to fulfil the quantified site-related requirements, the specific canister design for the repository site can be developed.

Adapted to the Norwegian DBD concept, the steps 1 and 2 of the methodology will be used. For a radioactive waste canister in general, three major safety functions can be identified:

1. Containment of the radioactive waste, e.g. as defined in IAEA SSR-5
2. Shielding of the radiation, e.g. as defined in IAEA SSG-1
3. Absence of criticality, e.g. as defined in IAEA SSG-14

In addition, three more design and concept specific safety functions can be defined:

4. Limiting temperature of the radioactive waste, e.g. as named in IAEA SSG-14
5. Limiting corrosion and gas production, e.g. as named in IAEA SSR-5
6. Operability, e.g. as named in IAEA SSG-1

The six listed safety functions have to be fulfilled by the canister during its required lifetime, which is separated in general in an operational part and a post-closure part. The operational lifetime starts with the encapsulation of the waste. The operational lifetime ends with the closure of the borehole. Simultaneously, the post-closure period starts. Within this period, the canister lifetime ends at a not yet clearly defined time. The end of the canister lifetime depends on the previously listed safety functions and will be analysed in the following sections. During both periods, the six safety functions have different roles and relevance, see Table 2-1.

Table 2-1: Canister safety functions and relevance within the disposal canister lifetime.

Safety function	Operational period	Post-closure period
Containment	Necessary	Partly/temporary, depending on the safety concept
Shielding	Necessary for personnel and environment, in combination with other components possible	Secondarily, to avoid safety-relevant radiolytic damage to other components
Sub-criticality	Necessary	Necessary
Limiting temperature	Needed for operability and operational safety	Needed to avoid safety-relevant damage to temperature-influenced components
Limiting corrosion	Needed but with reduced importance because of short time period	Needed to guarantee containment and to avoid/limit gas (pressure) generation for a certain period of time
Operability	Needed to guarantee operational safety and technical feasibility	Not needed, unless post-closure retrievability is required

2.2 Safety functions for borehole canister

2.2.1 Containment

In principle, the containment function must be ensured in such a way that the release of radionuclides into the biosphere is prevented to such an extent that the radiological limits specified in national laws are obeyed. For this purpose, the canister must have a sufficient sealing function and integrity under the specific impacts of the repository.

To guarantee containment, the canister has to prevent any release of radionuclides and the canister has to resist:

a) Mechanical impacts during the operational period, and
b) Mechanical impacts during the post-closure period.

Resistance to mechanical loads (static or dynamic) is strongly linked to operability. Providing containment for a not yet defined time of post-closure period is strongly linked to the corrosion resistance of the canister.

2.2.2 Shielding

To shield the ionising radiation emitted by the radioactive inventory, the canister must have sufficient shielding functions, taking into account the effects in the repository and during operation on the personnel and the environment. Essential parameters here are the choice of material and the wall thickness of the canister. Performance targets, such as dose rate during operation, will be defined by national law or licence conditions. Performance targets during the post-closure period depend on the design of the further barriers and their resistance against radiolytic or other damage. Barriers have to be in this way compatible.

In general, the regulatory requirements regarding the radiation protection of personnel and environment provide stricter standards than long-term related requirements for other EBS. Shielding does not necessarily have to be provided by the canister alone. To avoid conflicts with operability, other components can also take over the shielding function. In this case:

a) the canister guarantees shielding during the post-closure period to avoid safety-relevant radiolytic damage to other EBS/components, and
b) a transfer cask or over-pack guarantees shielding during the operational period to avoid/reduce impacts on the personnel and environment.

The technical solution (e.g. material selection) to achieve the shielding targets is strongly linked to the operability (e.g. allowed diameter) and the inventory.

2.2.3 Sub-criticality

Exclusion of criticality is a fundamental protection goal and must be demonstrated accordingly. Canisters are, therefore, to be designed in such a way that sub-criticality is ensured for the most reactive arrangement of the radioactive inventory under all loading conditions and taking into account the penetration of aqueous solutions into the canisters. Typically, a single canister is considered. Scenarios with an accumulation of radioactive inventory from several canisters always requires corrosion or damage scenarios and do not represent the reference case.

The avoidance of criticality must be demonstrated for the most reactive arrangement of the radioactive inventory.

2.2.4 Limiting temperature

The surface temperature of the canister must be limited in order to ensure operability and to exclude damage to the barrier function of engineered and geological (natural) barriers. The actual temperature depends on the design of the EBS. The inventory inside the canister also affects the temperature, so the limitation of thermal impact has to be considered for the inventory as well.

Heat generation is caused by the decay heat power of the radioactive inventory. Heat output of a canister can be directly controlled by the type and amount of the inventory. The canister surface temperature is also affected by the thermal properties of materials and the geometrical design of the near field.

During transport and operation, thermal standards for operability are defined e.g. by ADR/RID (Agreement concerning the International Carriage of Dangerous Goods by Road. Norway is a member). A maximum surface temperature of the canister of 85 °C is specified.

In order to protect the waste form and its components, e.g. Zircaloy fuel rod cladding tubes, much higher temperatures are tolerated. For HLW and SNF, temperatures were limited to 390 °C for pressurized water reactor (PWR) fuel elements, to 410 °C for boiling water reactor (BWR) fuel elements (DWK, 1986) and to 500 °C for the glass product of the moulds with reprocessing waste (Kienzler & Loida, 2001).

The maximal temperature for the protection of the host rock barrier is typically limited by national standards or can be derived from the thermal properties of the actual host rock or the EBS components.

2.2.5 Limiting corrosion

Corrosion is a natural process that converts a refined metal into a more chemically stable form such as oxide, hydroxide or sulfide. The conversion always includes a change of properties and may limit the time the safety functions or specific requirements for the canister are upheld. Thus, limiting corrosion is an essential contribution to guarantee, especially, the long-term safety functions. Additionally, corrosion processes and gas formation processes could have a negative impact on the containment function of the repository and the EBS. Corrosion depends on the actual geochemical environment, the presence of water and/or microorganisms as well as the used materials.

Limiting corrosion of the canister is important to:

a) Guarantee the required safety function during the defined functional period, and
b) Limit the gas production and gas pressure increase during post-closure period.

2.2.6 Operability

Operability during the operational period is strongly linked to the handling technology. This includes not just the design of load attachment points, material selection and dimensioning. It is strongly connected to the borehole design and restrictions to the external geometric dimensions.

The dimensioning of canisters must, on the one hand, take into account the geometrical dimensions of the radioactive waste, and, on the other hand, it is subject to restrictions by the handling and repository concept with regard to limitations in mass and external dimensions. On the one hand, repository canisters should be designed to be as compact and robust as possible with standardised external dimensions in order to simplify handling procedures and minimise the required drive-up volume; on the other hand, dismantling of fuel assemblies and/or cutting of fuel rods to reduce dimensions or volume should be avoided because of the very high technical effort involved and the complex radiation protection, safety and security issues associated with this. (Bollingerfehr, et al., 2020)

To guarantee operability during the operational period, the canister has to resist static and dynamic mechanical impacts during the operational period.

2.3 Processes affecting the canister

For the previously defined safety functions, the canister has to have specially defined properties or, in other words, a defined resistance against different impacts. The impacts on the canister vary over time. In general, the impacts can be grouped by process classes:

- Mechanical (and hydraulic),
- Thermal,
- Radiological, and
- Chemical/biological.

For each process, class-specific sources of impact can be identified or named. In the following step, the different impacts have to be linked to the safety functions. If possible, a quantification or, at least, an identification of a potential range has to be given afterwards.

Mechanical impacts or loads can be grouped into dynamic and static loads. Dynamic loads are expected mainly during operation. Relevant dynamic loads are accelerations, vibrations or impacts during handling (encapsulation and emplacement). Such loads result from normal operation. Additionally, dynamic loads can result from abnormal or accidental/incidental situations, such as dynamic loads from a dropdown. The impacts of external loads depend strongly on the technical design.

Static loads typically result from environmental impacts such as formation pressure, (static) water pressure, swelling pressure of sealing material, stacking loads of canisters inside the borehole, shear loads or thermally induced loads. The loads depend strongly on the environmental conditions and the borehole design.

Static loads during operation could result from the encapsulation process or the operation itself. The loads depend strongly on the technical design.

Thermal impacts result from the decay heat power and, during operation, from accidents such as fires. The thermal impact from the decay heat can be influenced by the inventory put in one canister. The rock temperature depends strongly on the environmental conditions and the depth. The fire temperatures depend on regulatory framework or the assumed burning load.

Radiological impacts result from the inventory of the waste. Gamma and neutron radiation are the most relevant properties. Both influence the needed shielding. The radiological impact can be influenced by the inventory put in one canister.

Chemical and/or biological impacts result mainly from liquids and their (aggressive) composition. Presence and composition of liquids is determined by the environment.

Table 2-2: Canister safety functions and relevant impacts/processes.

Safety function	Operational period	Post-closure period
Containment	Dynamic and static mechanical impacts	Static loads after emplacement End defined by corrosion effects functional period of other barriers
Radiation shielding	Inventory/Gamma and neutron radiation	Secondarily, to avoid safety-relevant radiolytic damage to other components
Sub-criticality	Inventory and load per canister	Inventory and load per canister
Limiting temperature	Inventory and load per canister	Inventory and load per canister Near-field materials and design Rock temperature
Limiting corrosion		Available liquids (amount and composition)
Operability	Dynamic and static mechanical impacts	

3 QUANTIFICATION OF CANISTER SAFETY FUNCTIONS

The safety functions of the canister were described in the previous chapter. In this chapter, the safety functions are quantified.

3.1 Containment

A safety function of the canister is the containment of the radionuclide inventory. Containment has to be provided first during the operational period. In this period, the canister needs to be gas-tight and has to withstand the handling loads during emplacement. During the operational and emplacement period, no corrosion loads which can affect the canister negatively are expected. During transport and handling in the disposal facility, the canister is put into a transfer- or supercontainer (cask), which protects the disposal canister from accidents such as dropping.

In the post-closure period, containment is further provided by the near-field EBS system and the host rock. For the host rock, the safety functions and target properties are described in the report “Host Rock Target Properties for Norwegian National Facility” (Hagros et al., 2021). The two host rock safety functions that consider isolation and containment are:

Safety function DBD-1: *“A safety function of the DBD host rock is to provide isolation from surface environment and human actions.”*

Safety function DBD-2: “*A safety function of the DBD host rock is to provide containment of the waste.”*

According to these safety functions, the long-term containment of the waste is a function of the host rock. To estimate the required canister lifetime, the thermal properties of the spent fuel and possible reprocessing waste can be used. The necessary canister lifetime is the time of the waste heat production. During this time, the canister has to provide containment. The thermal output of different fuel types according to (Bollingerfehr, et al., 2012) is shown in Figure 3-1. The horizontal axis shows the time after reactor discharge or reprocessing. The vertical axis shows the thermal output in kilowatt. The green curve shows the thermal output of CSD-V canisters with thermal active waste from reprocessing. This type of waste is considered here for the estimation of the time of containment because Norway also considers reprocessing of its spent fuel.

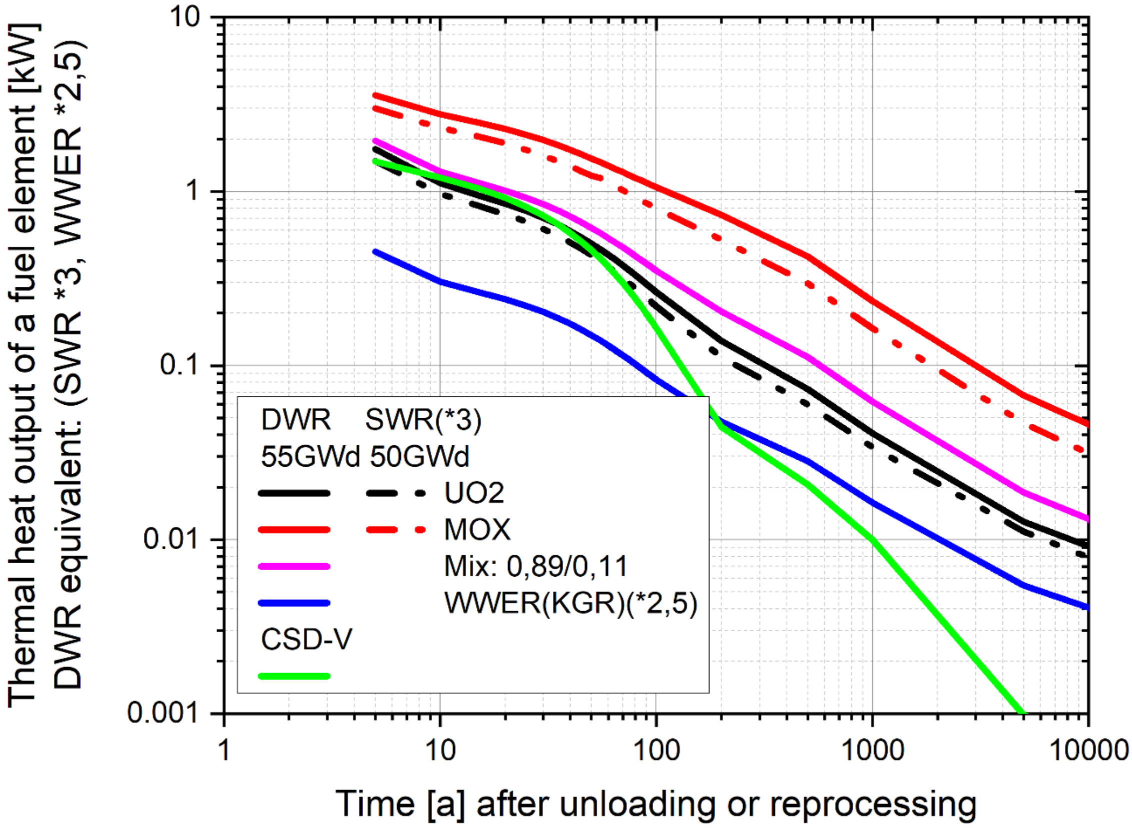

Figure 3-1: Thermal properties of spent fuel and reprocessing waste according to German data. Horizontal axis: time after reactor discharge or reprocessing. Vertical axis: thermal output in kilowatts (Bollingerfehr, et al., 2012).

The figure shows the heat output of the CSD-V canisters. The heat output decreases with time and reaches an output of 10 watt per canister after 1000 years. After 5000 years the heat output decreases to one watt per canister. After that the heat output is negligible. According to this, the canister has to provide containment for up to 5000 years and this needs to be considered in the canister design and material selection.

In the German joint research project "RESUS" (Becker, et al., 2020), criteria for the evaluation regarding the safety function containment of disposal canisters were made.

The first indicator is load-bearing capacity. The canister has to be constructed to bear all the static loads in the period of necessary containment. Therefore, it has to be shown that the strain in the canister is below the material property in question, the yield strength. For the canister design, the following formula can be used:

$$\eta = \frac{\sigma_e}{\sigma_p} < 1$$

With:

σ_e– existing stress
σ_p – permissible stress, $\sigma_p = \frac{R_m}{S}$
R_m – tensile strength
S – safety factor

The second indicator is stability. A canister for borehole disposal is a thin-walled structure and, therefore, has the possibility of failure through buckling. Buckling is the sudden change in shape of a structural component under load. Buckling may appear even though the stresses are well below those needed to cause failure in the material. So the canister design must prevent buckling due to axial pressure. The design verification for buckling problems is made according to EN 1993 Eurocode[1] 3.

$$\left(\frac{\sigma_{x,Ed}}{\sigma_{x,Rd}}\right)^{k_x} - k_i\left(\frac{\sigma_{x,Ed}}{\sigma_{x,Rd}}\right)\left(\frac{\sigma_{\theta,Ed}}{\sigma_{\theta,Rd}}\right) + \left(\frac{\sigma_{\theta,Ed}}{\sigma_{\theta,Rd}}\right)^{k_\theta} + \left(\frac{\tau_{x\theta,Ed}}{\tau_{x\theta,Rd}}\right)^{k_r} \leq 1$$

With:

$\sigma_{x,Ed} = \chi_x \frac{f_{yk}}{y_M}$ – dimensioning value membrane normal stress in meridian direction

$\sigma_{\theta,Ed} = \chi_\theta \frac{f_{yk}}{y_M}$ – dimensioning value membrane normal stress in peripherial direction

$\sigma_{\theta x,Ed} = \chi_\tau \frac{f_{yk}}{y_M\sqrt{3}}$ – dimensioning value membrane shear stress

$\sigma_{x,Rd}$ – permissible normal stress in meridian direction

$\sigma_{\theta,Rd}$ – permissible normal stress in peripherial direction

$\tau_{x\theta,Rd}$ – permissible membrane shear stress

f_{yk} – yield strength

y_M – partial safety factor

k_x, k_θ, k_r – interaction factor for buckling according to EN 1993 Eurocode 3-1-6

$\chi_x, \chi_\theta, \chi_r$ – reduction factor for buckling according to EN 1993 Eurocode 3-1-6

The third indicator is deformation resistance. The plastic deformation must be below the deformation limit of the canister material. Deformation resistance can be shown by the following formula:

$$\eta = \frac{\varepsilon_e}{\varepsilon_p} < 1$$

With:

ε_e – effective strain

ε_p – permissible strain (usually 5% for metals)

The last indicator is long-term durability. The canister will be affected by corrosion and has to be leak tight for at least 5000 years. Therefore, the canister must be sufficiently

[1] Eurocode series are European standards related to construction; Eurocode 3 is for the design of steel structures and provides guides for design and verification.

resistant against corrosion for this period, and its wall thickness must be large enough. The indicator for long-term durability is shown with the following formula:

$$\eta = \frac{D}{t * Cor} > 1$$

With:

D – wall-thickness

t – time (here: 5000 a)

Cor – degradation rate due to corrosion per year

3.2 Shielding

As described in Section 2.2.2, shielding of radiation has to be ensured to protect workers, population and environment. According to the ALARA principle of radiological protection, radiation dose has to be as low as reasonably achievable. A sufficient self-shielding canister would require a wall thickness so large that the handling and feasible disposal would be very challenging within the limited borehole dimension. Shielding does not necessarily have to be provided by the canister alone. Therefore, shielding for work safety in the operational phase is a safety function of a separate over-pack or transfer/transport cask used for transport and a safety function of shielding integrated in the disposal technology.

Dose rates used for the design of the over-pack or transfer cask can be taken from the *Agreement concerning the International Carriage of Dangerous Goods by Road (ADR).* The dose rates for the transport of radioactive materials by vehicles are given in ADR Volume 2, CV 33 (3.5). The term "under exclusive use" means that a vehicle carrying canisters with radioactive material only drives directly from sender to receiver and does not stop for any further loading.

"For consignments under exclusive use, the dose rate shall not exceed:

- a) *10 mSv/h at any point on the external surface of any package or over-pack, and may only exceed 2 mSv/h provided that:*
    - i. *the vehicle is equipped with an enclosure which, during routine conditions of carriage, prevents the access of unauthorized persons to the interior of the enclosure;*
    - ii. *provisions are made to secure the package or over-pack so that its position within the vehicle enclosure remains fixed during routine conditions of carriage, and*
    - iii. *there is no loading or unloading during the shipment;*
- b) *2 mSv/h at any point on the outer surfaces of the vehicle, including the upper and lower surfaces, or, in the case of an open vehicle, at any point on the vertical planes projected from the outer edges of the vehicle, on the upper surface of the load, and on the lower external surface of the vehicle; and*
- c) *0.1 mSv/h at any point 2 m from the vertical planes represented by the outer lateral surfaces of the vehicle, or, if the load is carried in an open vehicle, at any*

point 2 m from the vertical planes projected from the outer edges of the vehicle.“

As stated in Section 2.2.2, there can be an additional shielding requirement in the post-closure period to protect other barriers next to the emplaced canisters. In the Swedish-Finnish KBS-3 concept, this was set to a surface dose rate of 1 Gy/h at the canister surface (Raiko, 2012). With this requirement, excessive radiolysis of water outside the canister shall be avoided, which could lead to increased corrosion of canister materials or change the properties of the bentonite buffer surrounding the KBS-3 canisters. Whether this requirement is also necessary for a deep borehole disposal canister depends on the canister material and the sealing concept and, therefore, requires further research.

3.3 Sub-criticality

Sub-criticality of the Norwegian spent fuel inventory was described in the report “Feasibility of KBS-3 spent fuel disposal concept for Norwegian spent fuel” (Loukusa & Nordman, 2020). The metallic spent fuel only contains primarily natural uranium and a low quantity of fissile actinides produced due to low burnup of the fuel. Criticality with groundwater is not possible with natural uranium; therefore, criticality is not an issue for this waste type. Requirement for sub-criticality is not necessary for canisters loaded with spent fuel assemblies and rods from JEEP 1 and the HBWR 1st charge.

The oxide fuels in NND’s fuel inventory contain enriched uranium with an enrichment of up to 20%. For this fuel, criticality together with groundwater is possible and the canister has to ensure sub-criticality. According to the IAEA Specific Safety Guide No. SSG-27 (IAEA, 2014), safety limits for sub-criticality should be derived on the basis of one of two types of criteria:

- Safety criteria based on k_{eff} for the system under analysis, or
- Safety criteria based on the value of one or more control parameters, such as mass, isotopic composition, moderation, reflection, etc.

In nuclear waste disposal, safety criteria based on k_{eff} are commonly used. Sub-criticality can be expected if the effective multiplication factor k_{eff} is below 1. International standard (e.g. Sweden, Finland, France, Switzerland) is to limit k_{eff} to below 0.95 to ensure sub-criticality with adequate safety (see (Bollingerfehr, et al., 2020)). Sub-criticality has to be ensured for the most reactive credible configuration with optimum moderation and close reflection (Raiko, 2012). This usually requires the consideration of a breached canister filled with water. In NND’s inventory, a requirement for sub-criticality is needed for the canisters filled with assemblies or rods from JEEP II, HBWR 2nd to 4th Charge, HBWR 5th Charge, HBWR Booster and HBWR experimental.

If a higher safety margin is required in Norway, a lower value for k_{eff} can be used in the canister design.

3.4 Limiting temperature

Temperature has to be limited to protect the multiple barriers in the disposal system. These are the canister itself, the fuel components (e.g. fuel cladding), the near-field engineered barrier system and the host rock. Additionally, the temperature has to be limited for the operational phase for protection of workers. The operational phase protection can, however, be achieved with an additional over-pack or transport cask. For operational safety, the surface temperature of the canister should be limited to 85 °C according to ADR, as stated in Section 2.2.4.

The inside temperature of the canister has to be limited as well. In the work package 4 of the German joint research project “KoBrA” (Herold, et al., 2020), the inside temperature limits for multiple international disposal concepts in mined repositories were researched. The temperature limit for fuel assemblies or rods with Zircaloy cladding is usually set to 400 °C (Republic of Korea, Switzerland, United Kingdom and USA). Belgium sets the limit to 350 °C, Germany uses 390 °C, and France uses a higher limit of 450 °C. It is expected in this work that a limited temperature of around 400 °C for the Norwegian fuel assemblies or rods with Zircaloy cladding is also adequate. The reason of the temperature limit is to protect the cladding and to keep its barrier function against release of radionuclides.

Additionally, Norway has fuel assemblies and rods with aluminium cladding. In an alternative concept, it is intended in Norway to process the fuel rods with aluminium cladding and to put the fuel into stainless steel tubes. For aluminium-clad fuel, the Savannah River Technology Center set a temperature limit in their acceptance criteria for dry stored aluminium-clad fuel. The temperature criteria are set to 200 °C for aluminium-clad fuel. The reason for this temperature is the prevention of excessive degradation of the fuel in a 50-year-long storage period. Creeping of the cladding material and plastic deformation, distortion and rupture of the cladding shall mostly be prevented (Sindelar, Peacock, Lam, Iyer, & Louthan, 1996). For stainless steel cladding, no reliable values for the temperature limit could be found in literature research. Therefore, an approach to make an estimation for stainless steel cladding is made here based on the behaviour of metals at high temperatures. For verification, the calculation is also done for aluminium and Zircaloy.

According to IAEA TECDOC 1343 (IAEA, 2003), the major degradation mechanism for cladding materials during dry storage is creep. It is expected here that the degradation mechanisms for the cladding are the same as during dry storage. Creep is a metal behaviour were solid material moves slowly or deforms permanently under persistent mechanical stresses. Creep can occur even at stress levels way below the yield strength and increases with increasing temperature. In the end, creep leads to high plastic deformation and rupture of the material. Creep is a function of the material properties, exposure time, exposure temperature and the applied structural load. For the cladding materials discussed here, creep will lead to a loss of the barrier function of the cladding. Therefore, the temperature limit for the cladding should be below temperatures at which creep can occur. According to literature, creep can be expected when the temperature reaches temperatures higher than 0.3–0.4 times the materials melting temperature (Rösler, Harders, & Bäker, 2012). In the following table, the melting temperatures of aluminium, stainless steel and, as a reference, zirconium as the major alloying element of Zircaloy are given. Using these values, the estimated temperature limits are calculated.

Table 3-1: Temperature limit calculation for different cladding materials.

Material	Melting temperature	Calculated temperature limit for creep	Safety factor	Estimated temperature limit
	T_m [°C]	$0.3*T_m$ [°C]	S [-]	$T = (0.3 * T_m) / S$ [°C]
Aluminium	660	198	≈ 1	≈ 200
Stainless steel	1510	453	≈ 1.3–1.4	≈ 325–330
Zirconium	1857	557	≈ 1.3–1.4	≈ 380–400

In the table, the estimated temperature limits are given. To estimate them, the temperature limit for creep for the different materials was calculated first. After that, the calculated value for zirconium was compared with the given temperature limit of 400 °C for Zircaloy. Thereby, a safety factor of roughly 1.3 to 1.4 could be determined. With this, the estimated temperature limit of 325 to 330 °C for stainless steel was calculated.

Additionally, Norway considers reprocessing of its spent fuel and taking back the residue as vitrified waste. For vitrified waste from reprocessing, the temperature limit is usually set to a value of 500 °C. Contrary to the cladding material, this limit is not based on the mechanical properties of the glass. The basis for this limit is the temperature at which the glass matrix starts to segregate.

Also, a temperature limit is usually applied to the temperature of the canister outer surface. In work package 4 of the KoBrA research project (Herold, et al., 2020), the internationally used temperature limits for repositories in crystalline rock were researched. Sweden and Finland limited the surface temperature to 100 °C in the KBS-3 concept, the Czech Republic set the temperature limit to 95 °C. Germany limited the outer surface temperature of canisters to 100 °C in the Repository Site Selection Act (Standortauswahlgesetz, StandAG) for all host rocks until further research is done.

The purpose of the outer canister surface temperature limit in mined repository concepts is protection of other barriers in the direct periphery of the canister, usually the host rock and the sealing (buffer) system. Whether a fixed canister surface temperature limit is also feasible for deep borehole disposal shall be discussed in the following paragraphs.

In deep borehole disposal, the used disposal depths are greater than in mined repositories. The latter are usually planned for a depth between 400 and 1000 metres (Ikonen, et al., 2020). In the report on host rock target properties (Hagros et al., 2021), the host rock target property DBD-1c for deep borehole disposal states that *"The disposal zone should be more than a thousand metres below the ground surface." And evaluation factor "The disposal zone should be possible to locate at a minimum depth of 1500 m below the current ground surface."* The disposal zone in the deep borehole disposal concept can be expected to be in around 1500 to 3500 metres depth. The natural rock temperature at this depth is usually higher than in mined geological repositories (DGRs). According to the target properties report (Hagros, et al., 2021), in 3500 metres depth, borehole bottom temperatures from 50 °C to nearly 100 °C can be expected depending on the temperature gradient at the selected site. The remaining temperature difference between the actual host rock temperature and the temperature limit defines the acceptable heat output from the waste and the canister. The lower the temperature difference, the lower the acceptable heat output from the waste.

For the disposal in crystalline rock, microorganisms living in the disposal zone can affect the corrosion of canister materials. Bacteria and other microorganisms usually increase corrosion rates and can change the corrosion mechanism from uniform corrosion to localised corrosion. In Hagros et al. (2021), upper temperature limits for the living of microorganisms are given in Table 6-1. Sulphur-dependent bacteria have the highest upper temperature limit for living, 115 °C.

Another aspect is the protection of the sealing system. Seals made out of bentonite usually need to be protected from temperatures above 100 °C, which is one of the reasons a temperature limit of 100 °C is usually applied to crystalline rock. If there are bentonite seals placed directly in the canister surroundings, these need to be protected and a temperature limit of 100 °C for the canister needs to be applied. Usually in the deep borehole disposal concept, the sealing zone is placed several hundred metres above the disposal zone and no bentonite seals are located directly adjacent to the canisters. If this is also planned in the Norwegian concept, a strict temperature limit for the canister is not necessary. The first calculations regarding the temperature of sealing zones were done by (Mallants & Beiraghdar, 2021) for a deep borehole disposal concept planned in Australia. In that work, the temperature in a bentonite seal with a minimum distance of 100 metres from the disposal zone was calculated for different disposal systems at different depths. The results show that the temperature in the bentonite seal is not affected by the waste heat emissions and usually is around the depth dependent in-situ temperature. In the work (Mallants & Beiraghdar, 2021) it was concluded *“that a bentonite seal at 100 meters from the top of the disposal zone will remain at temperatures low enough to maintain long-term seal performance.”*

3.5 Limiting corrosion and gas production

It is necessary to limit corrosion and gas production by the canister materials. The canister must be leak tight for at least 5000 years and high gas pressure, which can affect other barriers such as the sealing or the host rock, needs to be prevented. This mostly affects the canister material. For the design of the canister and the material selection, two approaches are possible. The first one is the “corrosion allowance” concept, and the second is using a canister material that does not corrode or has negligible corroding material.

In the corrosion allowance concept, corrosion of the canister material is accepted and not prevented. Therefore, materials for which corrosion processes are known and predictable are chosen. Usually materials with uniform corrosion and no localised corrosion effects are chosen. Depending on the degradation rates, the necessary canister wall thickness can be calculated. For the corrosion allowance concept to be used, the canister wall usually must be thicker than in a concept where corrosion is prevented. In the deep borehole disposal concept, the outer diameter of the canister is fixed. If the wall thickness has to be increased, the inner diameter has to be reduced, and thus the payload or capacity of the canister will reduce. Materials used for corrosion allowance concepts are usually steels in different grades or cast iron.

In the corrosion prevention concept, a canister material with no or only negligible corrodibility is chosen. Examples of this material are noble metals copper and titanium. Usually canisters in geological disposal concepts are double walled. A thin corrosion barrier is placed above a thicker inner canister, which provides mechanical strength. In the deep borehole disposal concept, a canister made of non-corroding materials could possibly be thinner walled and, therefore, contain more waste, if the mechanical strength is adequate.

Later in this report possible canister materials and degradation rates will be discussed and possible wall thicknesses will be calculated.

To limit gas production, metallic corrosion should be limited. Gas production can also occur through decomposition of organic material. Decomposition can be thermal, radiological or chemical. According to this, there should be minimal use of organic materials in the canister design. Usual organic materials are polyethylene or graphite for neutron shielding or paint or surface coatings for corrosion protection.

4 CANISTER DESIGN

4.1 Dimensions

The canister is designed to contain all potential waste types. Thus, its dimensions are defined by the maximum length and diameter of the different SNF assemblies or HLW packages. The minimum inner diameter is 440 mm to cover a CSD-V canister, including an assumed annular space of 5 mm. The wall thickness is roughly calculated in the first step with 80 mm, resulting in an outer diameter of 600 mm. The length of the usable enclosure area is considered to be 3700 mm. A safety margin of 200 mm is added to accommodate the radii in the corners and some extra space for welding the top and bottom plate to the central tube. The radii in the corners should be considered large enough to have an even stress contribution over the inner surface. Figure 4-1 to Figure 4-3 illustrate the proposed canister design. Table 4-1 summarises the important geometric properties.

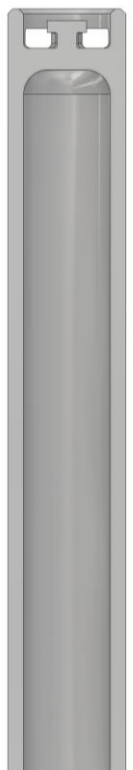

Figure 4-1: Half cut of the canister with encapsulation area.

Figure 4-2: Isometric view of the canister with showing the hook area.

Table 4-1: Dimensions of the DBD canister.

Property	**Value**
Outer diameter	600 mm
Inner diameter	440 mm
Wall thickness	80 mm
Outer length	4230 mm
Effective inner length	3700 mm

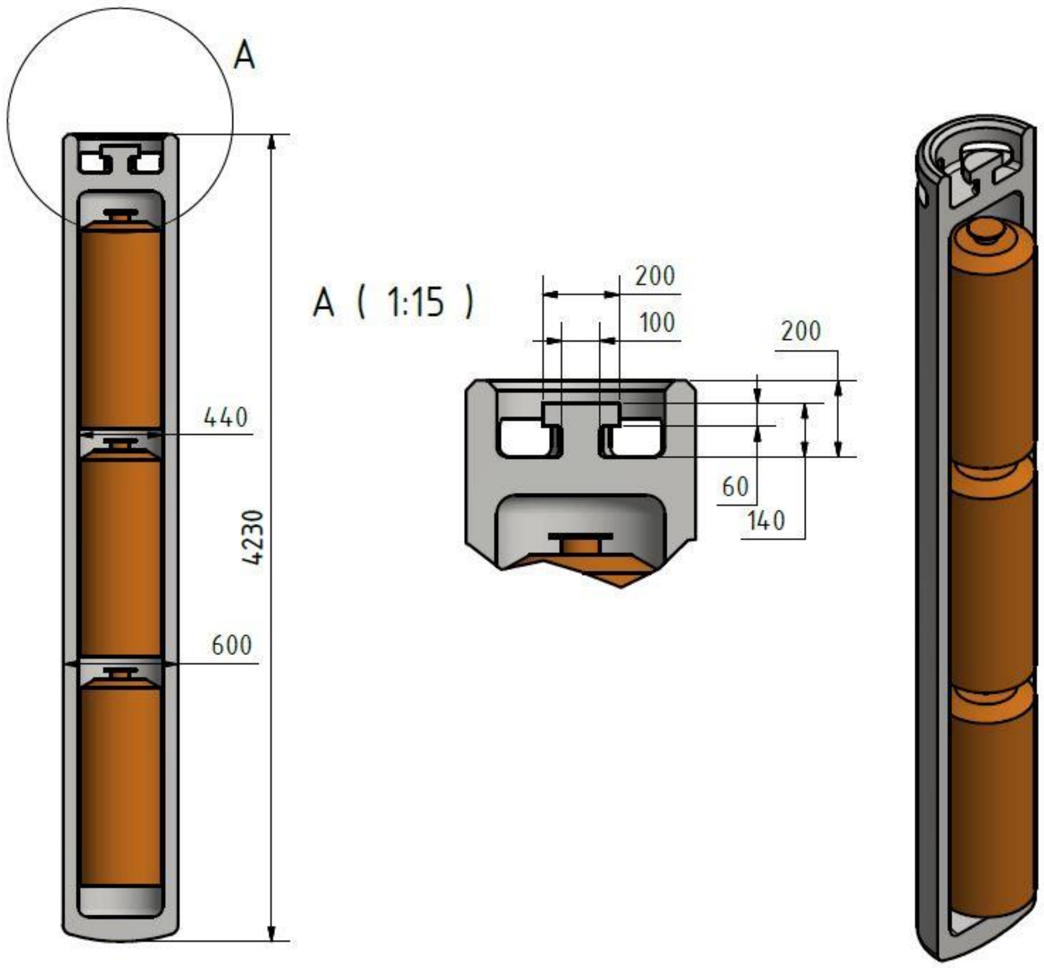

Figure 4-3: Half cut of the canister loaded with three CSD-V casks and including dimensions.

4.2 Static strength assessment of spent fuel canister

This section explores the mechanical integrity of the canisters. The plan is to dispose canisters in a deep borehole repository. The borehole is assumed vertical, 3500 metres deep and encased by a steel liner. The host formation is assumed to be crystalline rock. The borehole is filled with a fluid. This fluid contains high-density material. The minimum density is assumed to be 1300 kg/m³, based on (Kudla, et al., 2018). With this density, the isostatic pressure at 3500 metres is approximately 45.5 MPa. Due to the fact that the weight of the other canisters is unknown within the first iteration, isostatic pressure is the only load that is applied in the analysis. The hook load from the emplacement is neglected because it is considered much lower than the weight load of the canisters. The assessment estimates the maximum permissible load for the bottom canister.

At this point of the concept phase, a corrosion-resistant steel is considered. Austenitic steel grades have good corrosion properties. Nevertheless, the lower mechanical strength could be a problematic issue due to high loads. The mechanical strength also decreases under high ambient temperatures. On the other hand, the austenitic steel grades have a high elongation before break and high ultimate tensile strengths. For this reason, the $R_{p1\%}$ value is used for the tensile strength of austenitic materials. This is related to the good capability of the strain hardening of ductile materials with high break elongation. For this reason, many international standards, for example ISO 13800, use the 1% elongation as limit for plastic deformation. This will avoid the selection of strength values that will result in oversized constructions.

In the case that the tensile properties are not sufficient, a duplex steel grade is also possible to use. The pitting corrosion resistance is even higher. Due to the ferritic phase, the material also has better mechanical properties. Table 1 shows the material properties used for the calculation.

Table 4-2: Material properties acc. to DIN EN 10088-3.

Structure	ISO	UNS	Rp0.2%	Rp1%	UTS	A	Rp0.2%at 100°C	Rp1% at100°C
Austenitic	1.4435	S31603	200 MPa	235 MPa	500 MPa	35%	-	200MPa
Duplex	1.4462	S31803	450 MPa	-	650 MPa	25%	360 MPa	-

ISO - International Organization for Standardization; UNS - ***U**nified **N**umbering **S**ystem for Metals and Alloys; $Rp_{0.2\%}$ - yield strength at 0.2% deformation; $Rp_{1\%}$ - yield strength at 1% deformation; UT – Ultimate Tensile strength, A – elongation at break*

For the strength assessment, an ideal plastic material model is considered. The elongation is considered as infinitive as the load exceeds R_p.

The static strength assessment includes the assessment of plastification considering a combination of pressure and axial loads. A plastification of certain cross sections can occur during static load. As simplification, the canister is assumed as a pressure vessel. Under the given boundary conditions, this pressure vessel is considered safe against failure while exposed to ambient pressure.

The canisters are exposed to high weight load from the canisters stacked above. To accommodate the most conservative case, it is assumed that the canisters are stacked without backfilling on top of each other. With sealing and backfilling, some of the canister loads will be transferred to the casing and the load on the bottom canisters is reduced. The weight of an empty canister is approximately 4600 kg. The CAD calculated the weight with a given density $\rho = 8000$ kg/m³. The volume is approximately 1.13 m³. The maximum load in the CSD-V canisters is 1500 kg per unit. Based on the selected canister geometry it is assumed that, at most, 88 canisters have to be placed inside the borehole. For these given boundary conditions, the material has large amount of buffer for loads that are not considered. The canister is considered as safe with axial load from all other canisters stacked on top. The axial load is calculated using the number of canisters that are stacked and the average weight of the canisters. The weight load of all canisters is applied in the Finite Element Analysis, and the combined degree of utilisation is calculated with the pressure load.

While the canister is placed in the borehole, corrosion will occur. A uniform corrosion attack is considered over the outer surface canister. This corrosion will lead to a reduced wall thickness and higher stresses. A more detailed overview of the expected corrosion effects is given in Section 4.6. It is assumed that the plastic section factor will not change while wall thickness reduces. No notches or cracks are considered. The simulation is performed with the unmodified pressure loads and axial forces. The calculated degree of utilisation is visualised in Figure 4-4 for different points of corrosion attack. If the degree of utilisation is higher than 1, the stress loads are higher than the mechanical resistance of the canister, including safety factors, and result in a collapse. It should be considered that this value still includes the corrosion safety factor of 1.2. Hence, it can be assumed that the resistance against local stress risers due to pitting attack of small-localised areas is still sufficient.

The assessment shows the DBD canister stays intact under the given boundary conditions. The high stresses form in the junction between the top cover and the hollow cylindrical section as well as in the junction between the bottom cover and the hollow cylindrical section. Furthermore, the safety margins are large enough to compensate for a planar corrosion attack over time, see Figure 4-4. Within the named boundary conditions and assumptions, a planar corrosion of approximately 28 mm could be tolerated.

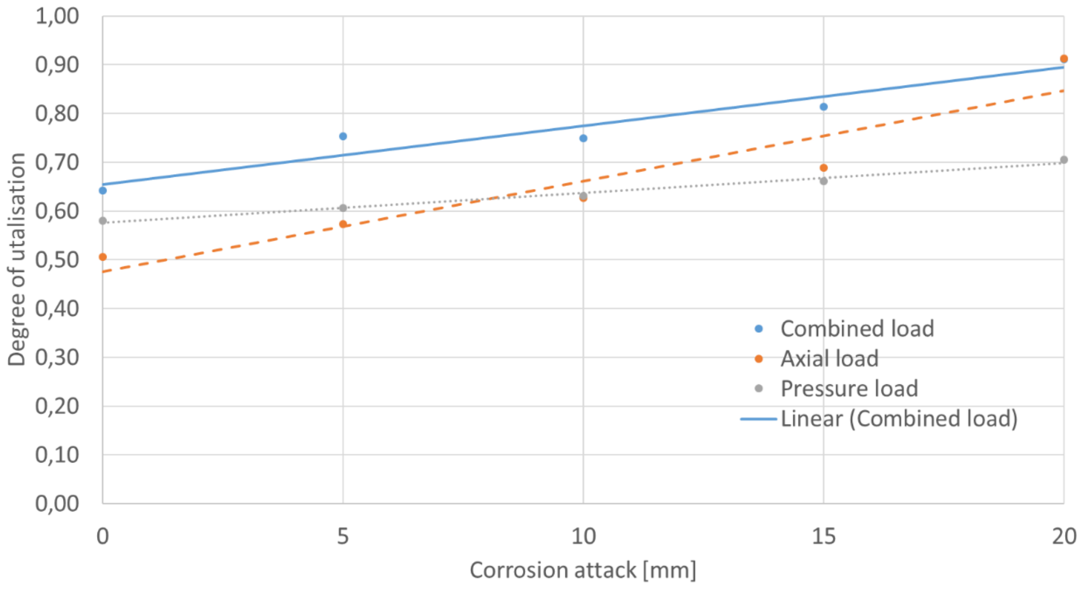

Figure 4-4: Evolution of the degree of utilisation while corrosion occurs.

The cylindrical sections that are close to the top and bottom lid are affected by lower stress concentrations. In this area, the lid can be joined to the tube without a sacrifice of structural strength. It is recommended that the central tube will be forged. The wall thickness is relatively high. This could lead to undetected material defects in the shell. Furthermore, it is recommenced to cold work (strengthening metals through plastic deformation below the recrystallization temperature) the outer surface of the specimen to reduce severity of pitting corrosion.

4.3 Manufacturing of the canister

The canister is welded out of three stainless steel pieces: bottom lid, central tube and top cover. The bottom lid is welded to the central tube during the production and before the canister is brought to the waste handling room (hot cell[2]). The top cover is welded in the hot cell after the canister is filled, see Figure 4-5 – Step 6.

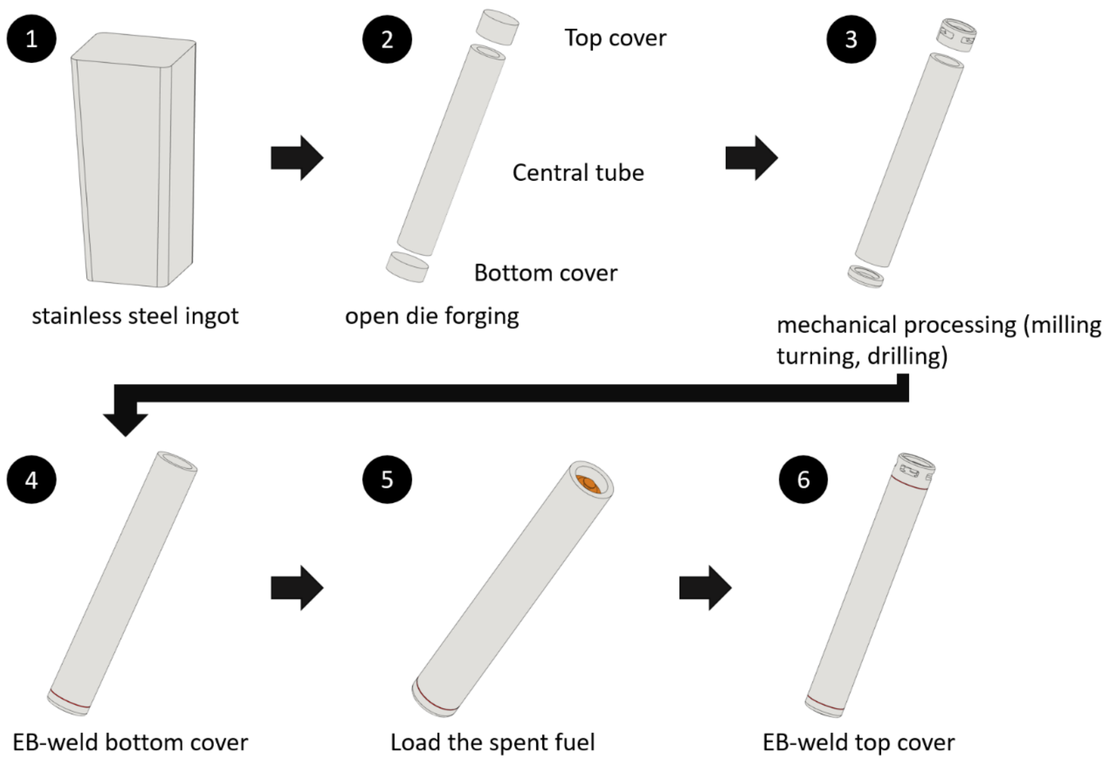

Figure 4-5: Illustration of the main steps during canister production and encapsulation.

The top and bottom part are milled out of a stainless open die forging. The forgings for the top and bottom part can be manufactured by a large quantity of manufacturers worldwide. In Germany, there are, for example, Dirostahl GmbH, BGH, Gustav Grimm Edelstahlwerk GmbH & Co. KG and many more. Other European countries such as Spain and Italy have similar capabilities to manufacture the forgings. There are currently no companies in Norway that can do this.

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[2] The term *hot cell* refers to a shielded nuclear radiation containment chamber or room in which radioactive material can be handled remote controlled while personnel can stay outside. The actual design of the hot cell depends on the handled radioactive material and the executed processes.

Figure 4-6: Example of open die forged disc (Canforge, 2021).

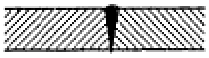
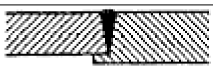
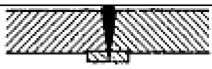
After forging the top cover and bottom cover, two semi-finished parts are created (Figure 4-5 - Step 2). Both have to be sent to a manufacturer, where the outer and inner contour is rectified according to the defined specifications, e.g. roughness (Figure 4-5 - Step 3). Before the contact surfaces to the central tube are manufactured, the cold work on the outer surface should be done. Due to the residual stresses that shot peening creates, there is a risk of slight deformation of the weld contact surfaces. The tolerances of that surface on both parts should be as tight as possible. Any gap that exists after joining the parts together will cause trapped air inside the weld. Therefore, the surface must be perpendicular to the cylindrical outer surface. The outer surface is for the welding jig that is later used to join the parts. The perpendicularity guarantees that both parts are aligned as well as technically possible. It is considered that a turning operation is sufficient to achieve the necessary quality of the surface. A possible company for manufacturing bottom and top cover in Norway is, for example, Aarbakke AS. According to their website, they have the necessary machines to manufacture the parts. The central pipe is more difficult to manufacture. The preferred method is to manufacture the tube in an open die forge with a central mandrel.

The hollow cylinder has the benefit that less material needs to be milled out and the transport is easier. On the other side, there are less manufacturers that can produce those hollow cylinders. It is also possible to manufacture the part as cylinder and bore out the core using a deep hole drilling process; see, e.g., Figure 4-7. If the zone with the forging defects is completely milled out and the material tests verify this, both processes are comparable. Afterwards the turning process should finish the outer contour relative to the inner contour. Both faces on the side need the same special care as the faces of the two other parts (top cover and bottom lid). The front and end faces of the tube do not need to be perpendicular to the whole outer surface. Only the orientation to the corresponding surfaces of top cover and bottom is important. If there are problems to manufacture those surfaces with a turning and milling process, grinding those surfaces with a dressed grinding wheel is an option.

Figure 4-7: Picture of a large-diameter deep hole drilling process (Shepcote, 2021).

The welding of the bottom part and central tube has to be done by electron beam welding (Figure 4-5 - Step 4). In detail, an I-weld is considered for the electron beam welding process, see Table 4-3. I-weld seam means the welding process does not consider additional support. Metal notches are not compensated. This method produces a simple and easy-to-manufacture geometry and requires a low manufacturing effort. A disadvantage is the reduced resistance against cyclic loads. For the considered application inside DBD canister, it is, however, unproblematic because the canister is statically loaded by ambient pressure.

Table 4-3: Illustration of the possible seam geometries for the canister (swissbeam, 2021).

	I-Seam
	I-Seam with centralizing Lid
	I-Seam with inlay

If the test welds show that there is a problem with spatter on the inside of the weld, an inlay could be considered. The electron beam can be focused directly above the inlay and melting only the parts of the canister. The inlay can be replaced with a centralising lid. This is necessary if the alignment with the jigs in the hot cell is not sufficient.

4.4 Quality control of manufacturing

The quality control of canister manufacturing should be considered in three steps. The first step is after the manufacturing of the forgings. The second step is after the turning and milling process. The last quality control step is performed after the electron beam welding is done.

The most important characteristics, besides the geometry, of the forging are the material properties. The needed minimum material properties and material compositions should be determined with manufacturing forge. The properties that the ISO defines can be used as reference for more specifications with tighter tolerances. The properties can be tested according to ISO-10204 with a WAZ 3.2. In this case, the manufacturer tests the properties and in addition an independent institution. The test must be conducted for every forging. The orientation and location of the test specimen is defined before. A recommendation for this process could be found, e.g., in the German KTA 3401.1 “Steel containment vessels - Part 1: Materials” (KTA, 1988), where the test procedure for components of light water reactors is defined.

After milling and machining, the most important property is the dimensional accuracy. The manufacturer and an independent institution must check all dimensions. This check must be conducted on every part, to avoid later problems in the hot cell. The main reason is the integrity of the welding process, which relies on the manufacturing quality of the part. Any deviation from the requested shape could lead to voids in the weld.

The first electron beam weld can be inspected outside the hot cell because it is done before the spent fuel is filled in. Before the first canister is manufactured, weld tests must be conducted to find the right operational parameters for the machine. After this, the reliability of the process is tested. If the technical reliability of the process is given, it can be contemplated that no additional check of the weld seams is necessary. It is assumed that a well-planned welding process can produce safe welds with a very high probability. The process is fully automated and repeatable if all parts meet the specifications. A sample size of approximately 10 specimens should be welded for material test purpose. The weld of these specimen should be tested according to an applicable guideline. For example, (KTA, 1988) contains the information about the specimen orientation. With this number of specimens, it is considered that the automated welding process is reliable. If the weld test data deviate from the material specification, the safety factor for the weld must be re-validated.

Even if the welding process is automated, it should be checked afterwards. Two options are relevant for this case. The first option uses an optical sensor that compares the current image with a pre-programmed failure case. The downside of this procedure is that the software has to learn which failures can occur. This is considered expensive for such a low quantity of large specimens. A visual inspection, using a laser instead of a camera, can perhaps make this process easier to implement, see e.g. (Victronic, 2021a). Apart from this, only visual inspection of the surface is possible.

For the second option, a supersonic weld inspection is considered. In comparison to the first method, this method can penetrate deep into the surface, see Figure 4-8. It can detect minor defects up to a minimal size of one millimetre (Vitronic, 2021b). This detection size is sufficient due to the high safety margin of the canister manufacturing/design.

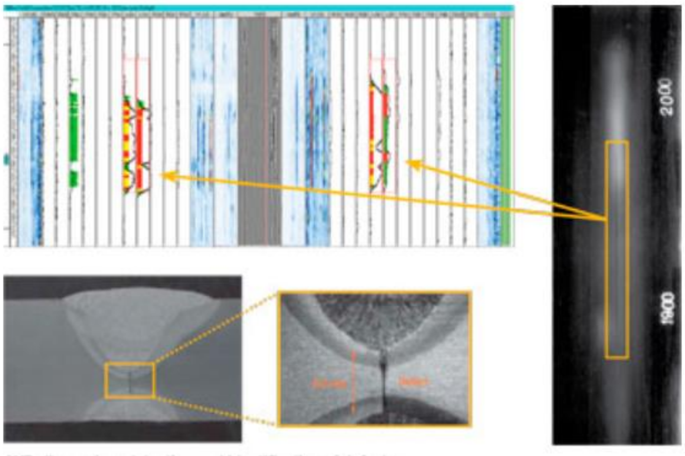


Figure 4-8: Example of ultrasonic weld inspection with evaluation (Olympos, 2021).

4.5 Canister welding process

4.5.1 Requirements

For the welding of the borehole canister, it is recommended to use an automated welding process. This is also needed due to the radiation of an unshielded canister. As welding of stainless steels may be challenging, the process should be defined very carefully.

According to (Gupta, 2012), carbides form during the welding process. For Grade 316 stainless steel, carbides form if the temperature is elevated for several hours. Due to the high wall thickness of the canister and low thermal conductivity of the material, this is possible if a process with a high heat input is used. In result, the formation of carbide will reduce the chromium content of the base material locally and reduce the corrosion resistance. Therefore, the specific heat input and the duration of increased temperatures have to be limited.

The low thermal conductivity and the high thermal expansion of stainless steel increases the risk of stress corrosion cracking. Microfissures can form in the weld deposit as it cools down and during solidification. They can also form in the heat-affected zone of the base material. To reduce this effect, a filler has to be used that creates a small ferrite content in the weld zone.

It is considered that the safest way to prevent stress corrosion cracking and contain the corrosion properties is to reduce the weld bead and heat-affected zone during welding. This will reduce the heat input and lead to a faster cooling of the remaining molten bead.

The welding process should be performed in vacuum or with an inert gas atmosphere. The oxygen, carbon dioxide and hydrogen in the air will reduce the weld quality drastically. For the considered AISI 316L base material, a subsequent heat treatment to relieve residual stresses is recommended by “a welding handbook”. However, welding tests have to be conducted with the material to define the welding process and define a constant outcome of mechanical and chemical properties.

4.5.2 Friction welding

Friction welding has a very low heat input in the base material. It is closer to forging than to welding. A possible way to join the parts together is rotational friction welding. However, taking the process values from (Switzner, 2017), the surface pressure in the weld is approximately 150 MPa for 316L stainless steel. The surface of the weld interface is approximately 130,690 mm². This results in a needed feed pressure of the friction-welding machine of 20,000 kN. This feed pressure exceeds the largest commercial machines by a factor of five. The friction stir welding process is not capable of welding these parts together. The required forces and torques are too high for such a small stir tool. All cases found for welding thick stainless steel ended up with around 15 mm plate thickness in several welding passes.

Overall, it is not considered as an economical solution to join those parts by friction welding, even if it is the best solution for the material properties.

4.5.3 Beam welding

Beam welding, especially electron beam welding has also a low heat input. Both parts are joined and fixed without a gap. Afterwards an electron beam is focused at the connection area and melts the metal in a small area. No filler is needed during the welding process.

The common kind of electron beam welding machines welds the work piece in a vacuum chamber. The vacuum is necessary for the electron beam generator to work. However, lately there are machines on the market that can work with a very coarse vacuum. In front of the vacuum generator, there are several chambers with increasing vacuum levels.

Commercial manufacturing machines achieve a penetration depth up to 300 mm in the base material. The “EBFLOW” machine from Cambridge Vacuum Engineering fulfils the recommendations that the concept requires. The penetration depth is sufficient, and the working speed is high. According to the manufacturer website, a weld is possible to be achieved within 10 minutes.

Figure 4-9: Electron beam generator (Camvaceng, 2021).

4.6 Long-term stability of the canister

4.6.1 Geochemical environment

Reactions of the metal can influence the long-term stability of the canisters, whereas reactions with gases, water and ions dissolved in the aqueous fluids must be taken into account. The reaction rates are influenced by the pH and Eh environment and microbial activities, which can also lead to the development of reactive phases. For the disposal zone, based on (Hagros, et al., 2021), it can be assumed that

- sodium and chloride dominated brines occur with minor contents of the cations calcium, potassium, magnesium and iron as well as the anions sulfate and hydrogen carbonate
- sulfides can be present due to microbial sulfate-reduction
- the content of dissolved salts is above 100 g/L up to about 350 g/L (cf. Figure 4-10)
- pH-values of approximately 8 can be expected as well as
- clearly negative Eh values, which prove an anoxic environment.

Carbon dioxide, hydrocarbons (in particular, methane), nitrogen and noble gases can occur as gas phases.

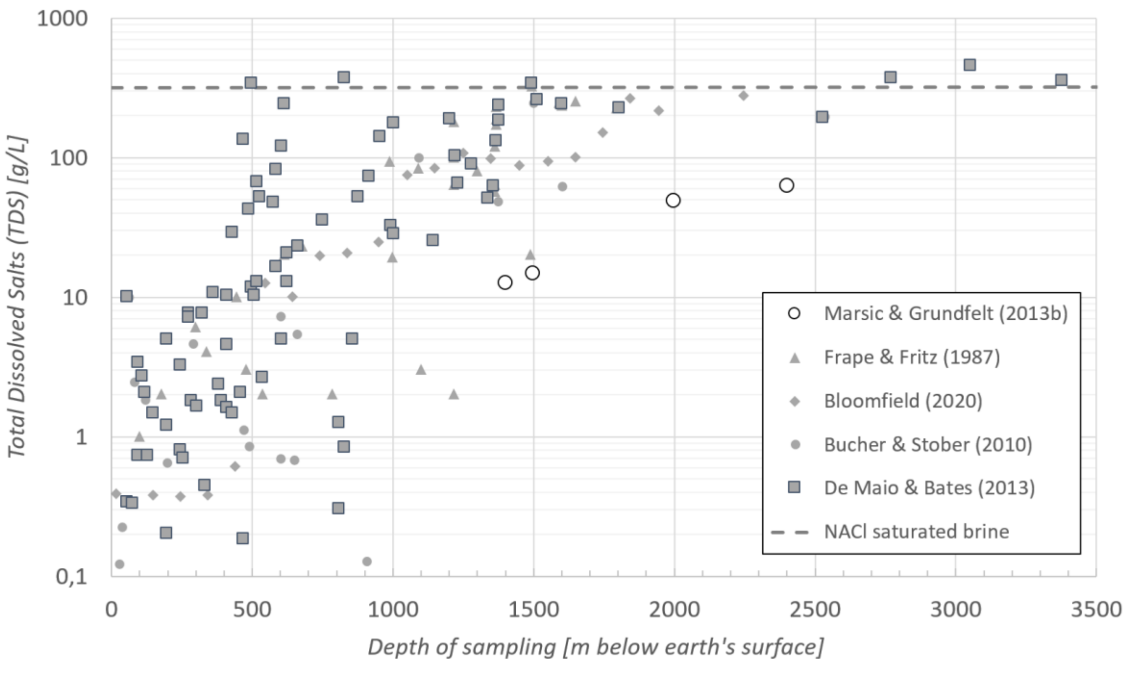


Figure 4-10: Literature data for TDS in crystalline rock formations as function of depth based on (Maio & Bates, 2013) (K.Bucher & Stober, 2010) (Bloomfield, Lewis, Newell, Loveless, & Stuarta, 2020) (Matsic & Grundfelt, 2013) (Frape & P.Fritz, 1987). The dashed, horizontal line illustrates the sodium chloride content of halite saturated brine.

During the construction, operation and closure of the borehole, various materials are used and emplaced into the borehole in addition to the canisters. This includes, for example:

- drilling or flushing solutions,
- a casing for borehole stabilisation purposes and
- a variety of backfilling and sealing materials.

The materials can react with the host rock, formation waters and gases and also with each other, and all the reactions can affect the stability of the canister. However, since there is currently no concept for backfilling the disposal zone and the amount and type of materials are not known, the following evaluation neglect these influencing factors. The analysis focuses on the host rock and brines. Theoretically, these fluids are available in an unlimited manner, and neglecting the other parts represents a conservative assumption. Potential positive impacts, e.g. passivation of steel based on high pH-values in concrete based backfilling, are ignored.

4.6.2 Corrosion

For the prediction of corrosion effects on the canister material in high-salinity environments, literature data are available from R&D activities related to repositories in salt. These data from US, UK and Germany are considered within the following analysis of corrosion effects as well. The type and the level of corrosion depends on the properties of the considered steel (e.g. composition and internal structure) and the (geo-)chemical environment (e.g. salinity and composition). In regard of the chemical reactions, corrosion can be divided in chemical and electrochemical corrosion. In regard of the characteristics, different corrosion processes can be described:

- Planar corrosion/general corrosion,
- Pitting corrosion,
- Crevice corrosion, and
- Stress corrosion cracking.

Planar corrosion of stainless steel, such as the considered austenitic steel and the DUPLEX steel, is very limited because of the passivation layer at the surface. The passivation layer forms from the oxidation of the metal surface in presence of water. E.g. (Mazeina, 2003) give an average corrosion rate of 1 µm/a for austenitic steel (1.4306) in Q-brine and saturated NaCl-brine. Similar values are given, e.g., in (Patel, et al., 2012) for anaerobic conditions or in (King, Sanderson, & Watson, Durability of High Level Waste and Spent Fuel Disposal Containers – an overview of the combined effect of chemical and mechanical degradation mechanisms, 2016), who highlight that the low rates (0.01 to 1 µm/a) can be expected in both, aerobic and anaerobic conditions. The low planar corrosion results in a slow weakening of the outer canister shell. From a mechanical point of view, the mechanical stability of the canister can be guaranteed for several thousand years. The numerical analysis as presented in Section 4.2 indicates a mechanical stability up to a wall thickness of approximately 50 mm. This corresponds to a corrosion of 30 mm of the material. Considering a loss of 1 µm/a or 1 mm in 1,000 years, the mechanical stability would be given for 30,000 years, theoretically. A theoretical lifetime of 10,000 years is still expected if the planar corrosion rate increases up to 3 µm/a. Within the DBD safety concept, containment over long term is guaranteed by the host rock and the engineered barriers. The containment function of the canister has a minor role and is needed only as long as the other barriers do not provide their full function.

Containment of the canister is not just defined by the mechanical stability. A local damage of the canister could result in a loss of containment function. Local corrosion, e.g. pitting corrosion, is more relevant for the containment in the sense of radionuclide release. Pitting corrosion can (theoretically) create local pathways though the steel and the containment function will be lost despite the mechanical stability. The pits could initiate cracking as well. However, it is known as well that the corrosion rate is not constant, see. e.g. (ASM, 2005).

(Dayal, et al., 1981) provide a Pourbaix diagram as a guide in defining electrochemical/pH conditions for which pitting will occur on carbon or low alloy steels in chloride solutions. Similar illustrations are, e.g., given in (King, Sanderson, & Watson, Durability of High Level Waste and Spent Fuel Disposal Containers – an overview of the combined effect of chemical and mechanical degradation mechanisms, 2016) and (Salleh, 2012). It is also known that an increasing salt concentration results first in an increase and then a decrease in the corrosion rate of iron; see, e.g., (Uhlig & Revie, 1985). The decrease is due to the decrease in the solubility of oxygen in the solution and, in the case of some salts, also to a decrease in the electrical conductivity.

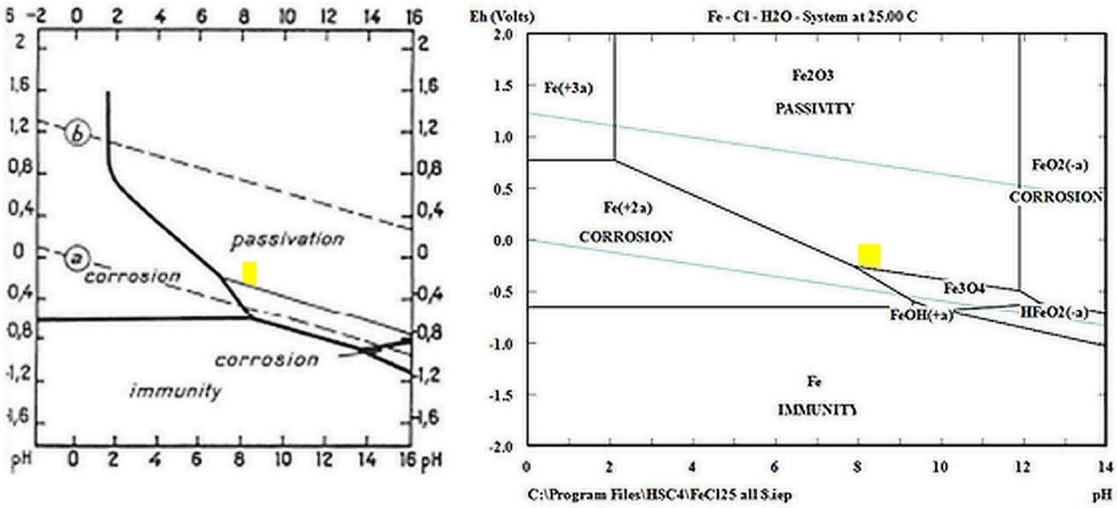


Figure 4-11: Potential/pH diagram for iron in chloride solutions, left: (King, Sanderson, & Watson, Durability of High Level Waste and Spent Fuel Disposal Containers – an overview of the combined effect of chemical and mechanical degradation mechanisms, 2016), right: (Salleh, 2012). According to the current state of knowledge, a pH value of at least 8 and a range for the Eh value of less than 0 to around -0.3 volts can be assumed (yellow squares).

Pitting corrosion occurs as a result of a local damage or weakness of the passivation layer. Chloride ions can dissolve the passivation and start the local corrosion of the steel. (King, Sanderson, & Watson, Durability of High Level Waste and Spent Fuel Disposal Containers – an overview of the combined effect of chemical and mechanical degradation mechanisms, 2016) highlight that the loss of passivation is connected to a characteristic electrochemical potential. Different experiments are known from literature, focusing on pitting corrosion. In conclusion, the suitability of austenitic steel is marked with a question mark or by some authors even denied, such as (Grauer, 1984). However, it is also known that the composition of the steel has a significant impact on the corrosion resistance. The higher the amount of alloying elements (especially molybdenum), the higher the resistance against pitting. Data show a wide range of pitting corrosion, as a function of the experimental conditions. Once again, the type of steel, the brine composition, temperature and duration vary within the experiments and give a wide range of results. Dayal et al. (1981) summarise data from several experiments. The observed pitting corrosion varies as a function of experimental setup. For most of the long-term experiments for 316L and 316 stainless steel, seawater was used. The experiments showed pitting corrosion with a wide range between rate of 0.035 to 0.5 mm/a. Typically the long-term experiments run between one and eight years. The results were approximated to a time of 1000 years. In every case, the approximation of the detected rates to the long term underlies the assumption of a constant corrosion rate over time. In this case, pitting corrosion would result in a loss of containment already after several centuries. In the absence of a selected site and known site conditions, only a rough estimation of the pitting corrosion risk for austenitic steel can be made. However, the transfer of these results to the DBD canister is only possible in a limited way.

DUPLEX steel (the second considered steel) provides a better resistance against pitting corrosion, see Figure 4-12. It is assumed that containment above 1000 years is possible but depends on the chemical conditions as well. If these are known, corrosion resistance or the needed steel type can be identified exactly. In the absence of reliable data, a prediction of the lifetime is not possible. A qualitative comparison is given in (Mundhenk, 2013). He investigated the corrosion resistance of different steel types in a geothermal application. The environmental boundary conditions are characterised by TDS of approximately 100 g/L, temperatures from 80 to 120 °C resulting from boreholes between 1,400 m and 2,500 m depth and in the granitic basement of the upper Rhine graben. Within the experiments, the austenitic steel showed no planar corrosion effects but a susceptibility for pitting corrosion. The DUPLEX steel, investigated in parallel, showed a higher corrosion resistance without the tendency of depassivation. The experimental results from (Mundhenk, 2013) underline the correlation between the pitting resistance equivalent number and pitting potential as presented in Figure 4-12.

(Liu, Gong, & Zheng, 2018) showed that the critical pitting temperature of Grade 2205 steel in high concentrated NaCl brine lies around 40 and 45 °C with a small dependency of the NaCl concentration. (Sandvik, 2021) gives for 2205 a critical pitting temperature of 80 °C or higher if the chloride content is below 1 wt.-%. Such conditions correspond to a salinity lower than marine salt water, see e.g. (Hagros, et al., 2021). For the expected high salinity and chloride content outside the DBD canister, pitting corrosion is not excluded but cannot be quantified satisfactorily. Factors influencing the corrosion behaviour are, e.g., the salinity and chloride content of the water, pH and Eh value and temperature. In a certain way, the parameters can be influenced by defining tolerable limits and considering them in the site selection.

(Hagros, et al., 2021) state that the risk of corrosion is connected to microbiological corrosion. It can be assumed that this influence is small due to the low activity of microbes in highly saline solutions and the low supply of nutrients, whereby, in the case of deep borehole disposal, the low borehole and thus backfill volume must also be taken into account (cf. King et al. 2021). In addition, technical measures can increase the resistance of the canister against corrosion. Cold working of the surface will lessen the size and number of surface defects and will reduce the possibility of a pitting corrosion attack. In addition, (King 2009) describes that the low pH of the solution that is found near to concrete embedded stainless steel, creates an environment that prevents pitting corrosion.

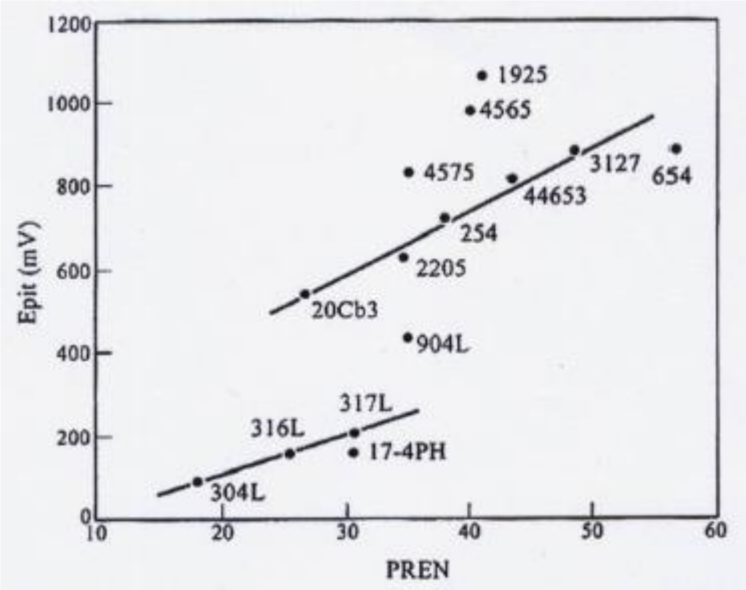


Figure 4-12: Correlation between the pitting resistance equivalent number and pitting potential for various austenitic, duplex and superaustenitic stainless steels (King, Sanderson, & Watson, Durability of High Level Waste and Spent Fuel Disposal Containers – an overview of the combined effect of chemical and mechanical degradation mechanisms, 2016).

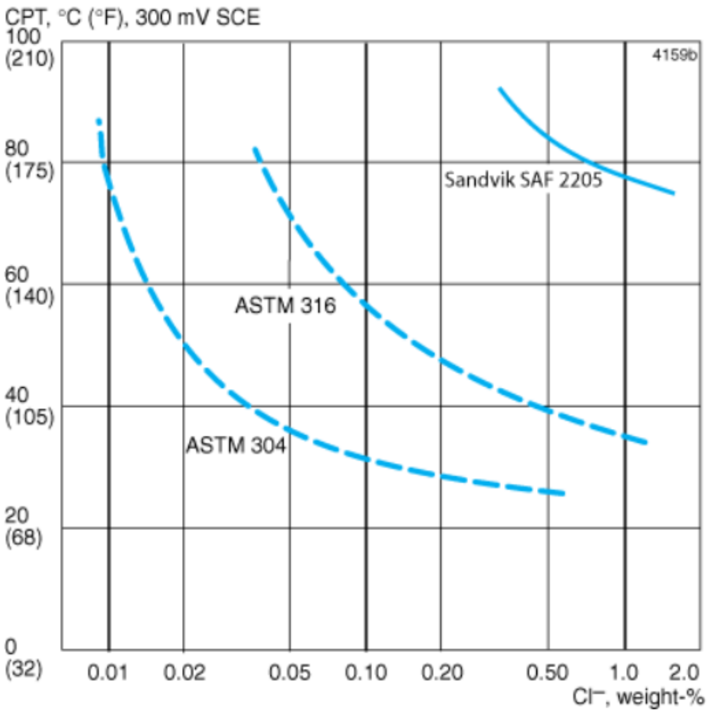


Figure 4-13: Critical pitting temperatures (CPT) for SAF 2205™, ASTM TP304 and ASTM TP316 at varying concentrations of sodium chloride (potentiostatic determination at +300 mV SCE), pH 6.0, based on (Sandvik, 2021).

5 INTERACTIONS WITH THE DEVELOPMENT OF BOREHOLE SEALING

Two parallel interacting development projects took place with respect to advancing the borehole disposal concept for NND. These two projects were Canister Design (this report) and Borehole Sealing (report to be published in the fall of 2021). The interactions are summarised in the following.

Input from Canister Design project to Borehole Sealing project:

- Geometry: canister design from "inside to outside", CSD-V canister with the largest diameter (430 mm), plus 5 mm annular space, result in 440 mm inner diameter, the assumed wall thickness of 80 mm result in 600 mm outer diameter of the canister, the inner length of the canister is defined by 3900 mm (3700 mm for longest SNF element and 200 mm for welding and transition), a second, smaller canister (length 3200 mm) is possible too, for optimisation of remaining free area for smaller SNF elements
- Borehole diameter: the canister diameter of 600 mm plus an annular space of 50 mm (assumption result in an inner borehole diameter of 700 mm)
- Size of the disposal area: the described geometry results in 88 canisters for disposal without reprocessing, the expected disposal zone length is approximately 460 m (including one metre distance between canisters); in case of reprocessing the number of canisters and the disposal length reduces.

Input from Borehole Sealing project to Canister Design project:

- Casing: the borehole will almost certainly be cased in the disposal area, different possibilities are given, the most realistic scenario is the following:
    - Casing the entire borehole
    - Disposal in a cased borehole
    - If necessary, place a cap above the last canister
    - Investigate possibility to remove all remaining casing at the sealing location or at least mill out sections of tubing
- Stacking: The canisters are exposed to high weight load from the stacked canisters above. To accommodate the worst case, it is assumed that the canisters are stacked without backfilling on top of each other. The weight of a single canister is assumed to be 4600 kg plus 1500 kg from the waste (3 times CSD-V); the stacking of the 88 canisters does not result in a breakdown of the bottom canister.

6 PROCESS FOR CANISTER MANUFACTURING AND ENCAPSULATION

In this chapter, the process for canister production and encapsulation is described. Before the encapsulation, the fuel is possibly treated, but it is currently unclear if it is reprocessed, the cladding material is changed, the metallic uranium is transformed to uranium oxide or if the fuel stays as it is.

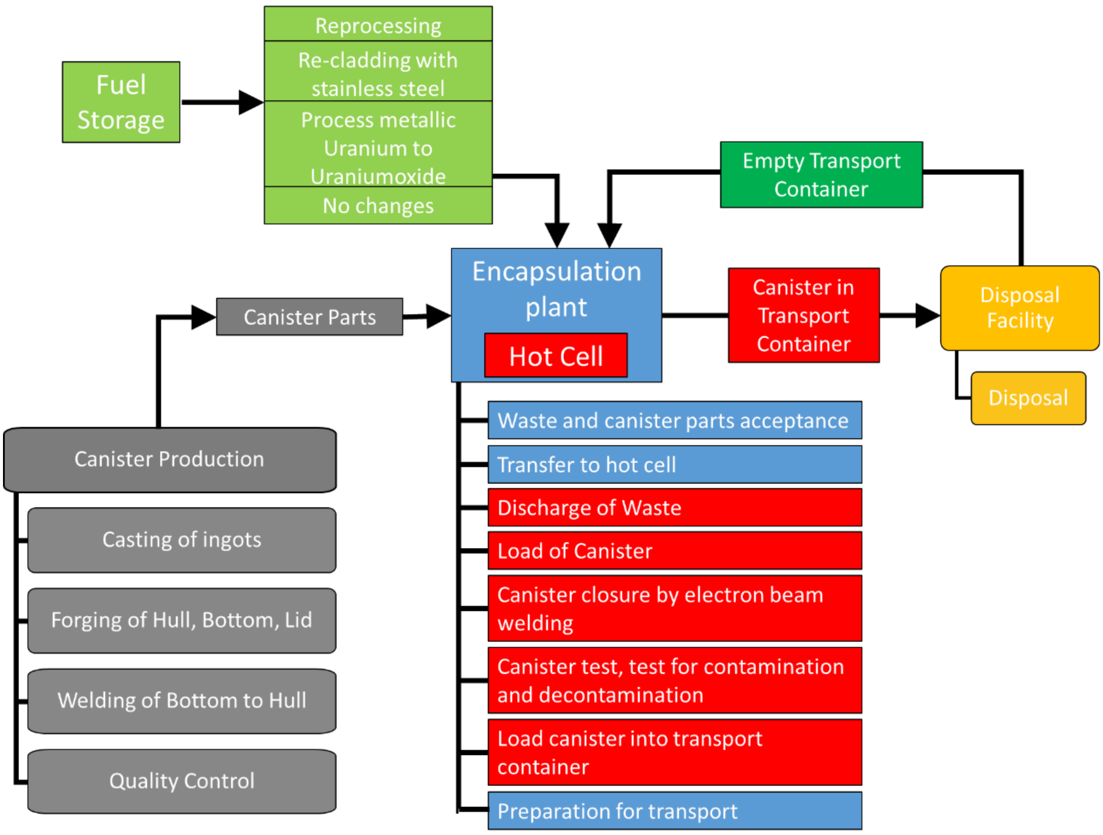


Figure 6-1: Graphical illustration of the working steps between canister production and disposal.

6.1 Canister manufacturing process

Production of wrought material

The first step of canister production is the production of wrought material such as casting ingots for the forging or the production of tubes. In this step, the material composition has to be tested by taking samples from the wrought materials.

Forging of hull, lid and bottom

In the next step, the canister hull, bottom and lid are forged and machined to the final dimensions. For the planned closure of the canister by electron beam welding, the canister parts need to be machined with high accuracy and little tolerances. After the forging additional samples have to be taken to test if the material properties conform to the specifications in the canister design. To increase the resistance against pitting corrosion, it is possible to additionally treat the components with a cold working method such as shot peening.

Welding of bottom to hull

In this step, the canister bottom is welded by either electron beam welding or other welding techniques, such as metal inert gas welding to the hull. After the welding, the weld should be machined and treated. Additionally, non-destructive testing is necessary to test the canister hull and the weld to detect defects. For the testing of the weld, non-destructive testing such as ultrasonic inspection or X-ray inspection can be used. In this way, only the closure weld would be performed inside the hot cell of the encapsulation plant.

In addition to welding the canister bottom to the hull in the canister production facility, this step can also be performed in the hot cell using the available electron beam welding equipment and is described in Section 4.2.

Quality control

During canister production, quality control measures have to be taken. The results of the testing have to be documented, and the documentation has to be shipped together with the canister parts to the encapsulation plant.

6.2 Encapsulation process

Waste and canister part acceptance

The radioactive waste will be delivered in transport casks. If the predefined acceptance criteria are fulfilled, the transport casks will be briefly stored in the encapsulation plant before their transfer to the hot cell. Regarding the canister, the first working step in the encapsulation is the delivery and quality assessment. This includes a check of the documentation from the canister production. If the predefined quality assurance plan is complied, the canister parts are accepted and stored. If the canister parts fulfil the quality requirements, they can also be transferred to the hot-cell facility.

Transfer to hot cell

Because of the radiation, the canister loading can only take place inside a hot cell, which is adequately shielded. First, the canister parts are transferred to the hot cell. If the welding of bottom to hull shall also be done in the hot cell, this weld (and the related test) is transferred first without any radioactive material inside the hot cell to simplify the processes. In this case, the shielding of the hot cell is only used to shield the X-rays from the electron beam welding equipment during the welding process. After the welding, the weld between hull and bottom should be inspected with non-destructive techniques, such as ultrasonic or X-ray. Machining the weld is not required when electron beam welding is used. It is recommended to first do the welding on all necessary canisters before radioactive material is brought into the hot cell.

After the canisters are prepared, the first radioactive waste can be transferred to the hot cell and locked in there until the canister load begins.

Discharge of waste

When the wasted is locked in the hot cell, the transport casks can be opened and the waste is discharged. The discharge of the transport casks should be placed directly near the canister load so that no large distances need to be travelled with the open radioactive waste.

Load of canister

In this step, the waste is loaded into the disposal canister. The open disposal canister is then brought to the welding station.

Canister closure by electron beam welding

The canister closure weld is made by electron beam welding. Therefore, either the canister has to be brought into a vacuum chamber or a vacuum hood has to be placed around the weld zone, because vacuum is needed for the electron beam welding process. After the electron beam welding process, no machining of the canister is necessary.

Canister test, test for contamination and decontamination

The canister weld has to be qualified to be leak tight and to secure the containment of radionuclides over the necessary time. Therefore, a test of the canister weld is necessary. The test of weld is usually made with non-destructive testing methods such as ultrasonic testing or X-ray.

Due to the low number of only 88 weld seams, including another quality assurance method seams feasible. The quality assurance of the welds can also be done by strictly monitoring the process parameters of the welding process. Therefore, it is necessary to produce some prototypes with the same welding equipment and to test these with destructive and non-destructive testing methods. With this approach, the process parameters necessary to produce suitable and correct canisters shall be determined. When using these process parameters in the welding process, it seems statistically possible that, with the small amount of welds, all welds should be working and leak tight.

In addition to the test of the welds, a test for contamination on the canister surface is necessary. Also a possibility to decontaminate the canister is necessary inside the encapsulation plant.

Loading of canister into transport casks

The finished canister has to be placed inside a transport cask for shielding and protection from mechanical impacts during transport. The canister is loaded into the transport cask, and the transport cask is subsequently made ready for the transport to the disposal facility.

Preparation for transport

The loaded transport cask is docked off of the hot cell and turned into a horizontal position. After that, the transport cask is brought outside the encapsulation facility and transported to the disposal facility for disposal.

6.2.1 Technical properties of encapsulation facility

Inside the hot-cell facility, different equipment is needed to execute the relevant working steps. For the handling of waste, empty and filled disposal canisters and transport cask lifting equipment is needed. For the loading of waste into disposal canisters, manipulators can be used. If the spent fuel is directly placed into the disposal canisters, a lifting capacity of around 50 kg is necessary for the manipulators. If vitrified waste inside CSD-V canisters is considered, a higher lifting capacity of around 600 kg is necessary. Lifting of empty disposal canisters and its components and lifting of filled transport casks gantry cranes can be used. A lifting capacity of 10 tonnes is enough for this purpose. The heaviest component that needs to be lifted is the shielded transport cask as described in Section 6.3. For the transport cask itself, no lifting inside the hot cell is necessary; it is only docked to the hot cell and loaded. Thereby, it seems possible that mobile lifting equipment, such as mobile cranes, can be used for this purpose. The necessary lifting capacity would be around 60 tonnes.

For the encapsulation process itself, the electron beam welding equipment, as described in Section 4.5.3, needs to be set up inside the hot cell. Also, either a hood or chamber for the necessary wrought vacuum needs to be placed around the welding equipment.

According to the QA concept, the weld zone is tested by ultrasonic testing to confirm the integrity of the welds and canisters. In addition, it can be required to weigh the canister and to do testing for the radiation dose on the canister surface and in around a 1-metre distance from the canister surface. Also, a test for surface contamination will be necessary. This can be performed by taking smear samples with a glove box and direct evaluation of the samples. Alternatively, the samples can be taken with a robot. If surface contamination is found, the disposal canisters have to be brought into a decontamination cell and be decontaminated. Decontamination can either be performed by dry treatment with the help of a robot or by high-pressure water spraying inside the decontamination cell.

The hot cell is equipped with at least one access point (including air lock) to allow access and bringing in of components, parts of the disposal canister as well as the spent fuel. The dimension of the air lock must be large enough for empty disposal canisters with a diameter of 0.6 metres and a length of around 4 metres. In addition, one lock where the transport cask can be docked on is necessary. It should be equipped with a lock such as a borehole lock, as can be seen in Figure 5-2.

Besides the technical processes especially needed for encapsulation, the existing regulatory framework defines the design and complexity of such a facility. In this context the Strålevern Hefte 2018:33, Pollution Control Act (forurensningsloven) and IAEA GSG-7 have to be highlighted:

“In order to avoid and limit pollution and waste problems, the technology shall be used that, based on an overall assessment of the current and future use of the environment and of economic conditions, produces the best results.” Pollution Control Act, section 2

“The undertaking shall ensure that radiation shielding and other safety equipment, such as personal protective equipment and technical safety systems, is available where necessary.” (Strålevern Hefte 2018:33)

“Where the physical design features of a facility do not provide sufficient containment or shielding of radioactive material, additional engineered controls using facility systems and components should be used to protect individuals. For example, adequately designed and properly controlled ventilation systems are an effective means of minimizing exposure in workplaces prone to airborne contamination, such as in underground mines and in buildings in which dry processing of radioactive minerals is carried out. Installed fume hoods, glove boxes and manipulators are also examples of engineered controls.” IAEA GSG-7

Additionally, it is currently not known which auxiliary safety requirements are set for such a nuclear facility. It is expected that the building in which the hot-cell facility is placed has to withstand impacts like airplane accidents or earthquakes.

6.3 Technical properties of the transport cask

For the transport of the borehole disposal canister to the disposal site, a transport cask is necessary. In Chapters 2 and 3, it was already mentioned that the safety functions “shielding and limiting temperature” are partly not fulfilled by the canister itself and are, therefore, safety functions of the transport cask. The transport cask also gives mechanical protection to the canister during transport. A similar transport cask was designed for the German BSK-3 concept for the disposal of spent fuel and reprocessing waste in a salt dome in the R&D project DENKMAL (Filbert, et al., 2010). The transport cask was also built as a prototype and used for demonstration tests in the same project.

The transfer cask consists of a body made of ductile cast iron. On the ends, two cask locks made of stainless steel are placed. On the outside, four trunnions are place for the handling of the transport cask. The cask wall thickness complies with the requirements set in the Denkmal project (Filbert, et al., 2010) regarding mechanical strength and neutron and gamma radiation shielding (see Table 6-2). In the cask wall, polyethylene rods are placed in two rows for further neutron shielding. In the cask locks, polyethylene plates are used for neutron shielding. Figure 6-2 shows the transport cask design.

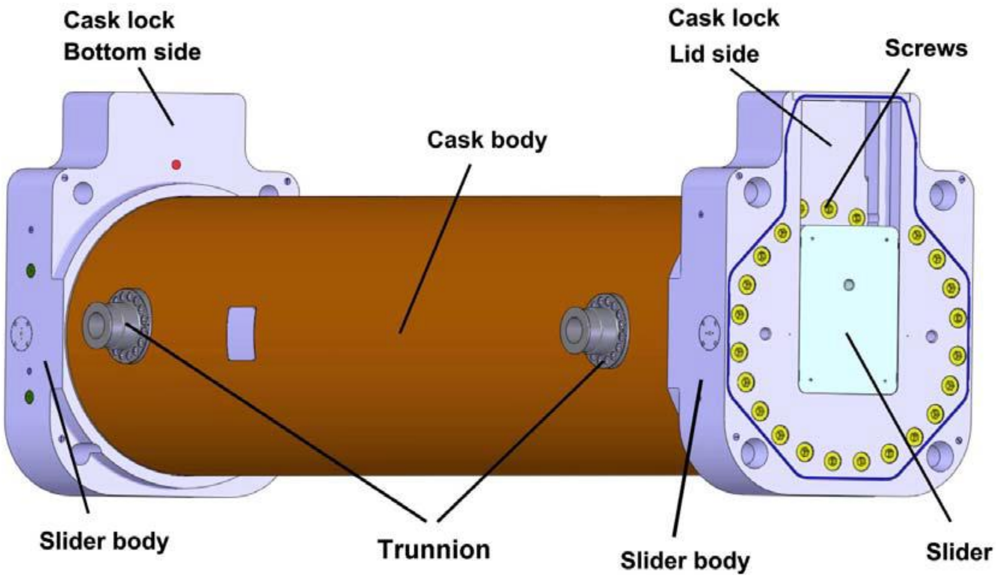


Figure 6-2: Transport cask for the disposal canister (Filbert et al., 2010).

The lock sliders in the cask locks operate according to the drawer principle and are guided in a spring-groove system. The locking sliders are secured by two locking studs, which prevent accidental opening. To open the transport cask, a counterpart lock is required. This is at first the borehole lock placed over the disposal borehole. Also, a lock is required in the encapsulation plant for canister loading. Further, the disposal equipment must be able to open the lock on the second canister side to insert a grapple or similar emplacement equipment. The canister itself has no control device to open its locks; therefore, the canister can only be opened in the encapsulation plant or at the disposal site. Figure 6-3 shows the borehole lock for reference.

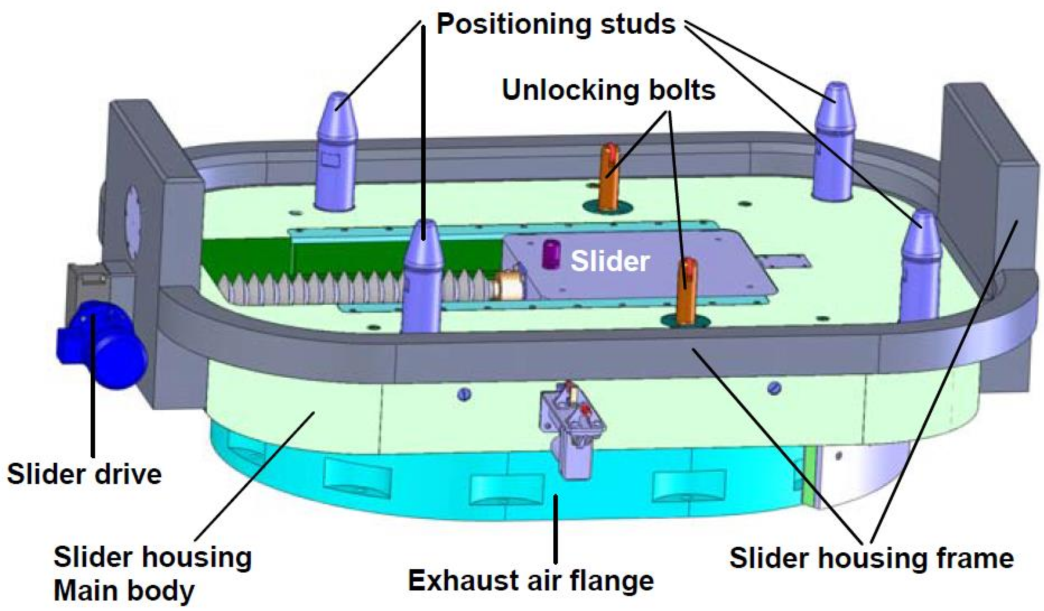


Figure 6-3: Borehole lock (Filbert et al., 2010).

The transport cask by (Filbert, et al., 2010) was made for the BSK-3 canister, which has a smaller diameter than the now designed canister, see Table 6-1. Therefore, some changes in canister dimensions are required. The following table shows the primary dimensions and a first assumption of the new dimensions. The primary transport cask design had a weight of 45,700 kg. The dimensions of the transport cask are given in Table 6-1.

Table 6-1: Dimensions of the transport cask, (Filbert et al., 2010).

	Primary Design	Changed Design
Canister Diameter [mm]	440	600
Inside Diameter [mm]	445	605
Outside Diameter [mm]	1305	1465
Cask Length [mm]	5570	

Due to the larger canister diameter, the transport cask for the canister designed in this report will have slightly larger outside diameter. The length is considered the same as in the primary design. For shielding, the requirements in Table 6-2 were fulfilled with the canister and reviewed by calculations in the Denkmal project (Filbert, et al., 2010).

Table 6-2: Dose rates of the transport cask (Filbert et al., 2010).

Location	Dose Rate [mSv/h]	
	Normal Operation	Malfunction
Surface	≤ 2	-
2 m from the surface	≤ 0.1	-
1 m from the surface	-	≤ 10

The dose rates for normal operation in Table 6-2 are taken from ADR Volume 2, CV 33 (3.5), as also stated in Section 3.2 of this report. The dose rate for malfunction is taken from the ADR Volume 2, Section 6.4.8.8. In that section of the ADR, the design requirements for type B(U) packages subjected to the tests specified in ADR for normal use and accident conditions are described.

The following drop scenarios were used in the Denkmal project (Filbert, et al., 2010) for the mechanical strength review. The canister fulfilled all the requirements in the Denkmal project:

- 5.0-m drop in the encapsulation plant in a vertical position (bottom flat drop) onto a stationary shock absorber,
- 3.0-m drop in the encapsulation plant in a horizontal position (surface line drop and slap-down drop) onto a stationary shock absorber,
- 3.0-m drop in the vicinity of the underground borehole lock during the handling in the emplacement device in horizontal position (surface line drop, including slap-down drop) onto a two-part stationary shock absorber,
- 0.5-m bottom edge drop (transfer cask centre of gravity vertically above the impact point) onto the borehole lock during the handling in the emplacement device,
- 0.6-m bottom flat drop onto the borehole lock during the handling in the emplacement device.

For thermal requirements, the transport cask was made to guarantee a surface temperature of 85 °C at a surrounding air temperature of 30 °C and avoiding direct sunlight. Also, the transport cask was made to protect the load in case of fire for 30 minutes by flame temperature of 800 °C.

For the road transport of spent fuel and reprocessing waste, transport casks of type B(U) according to ADR are usually used, for example the German CASTOR® Casks. Requirements for type B(U) packages are specified in Section 6.4.8 of the ADR. If transport of the waste is necessary on public roads between the encapsulation plant and the disposal site, stricter requirements than currently fulfilled by the transport cask have to be met. The requirements according to Section 6.4.8 of the ADR for shielding, temperature limit and containment are fulfilled by the transport cask. Further research will be required if it is also possible that the transport cask fulfils the test conditions for demonstrating ability to withstand accident conditions in carriage according to ADR 6.4.17, where, for example, the required drop heights are higher than the ones used in the current cask design.

6.4 QA/QS during canister loading and closure

It is expected that only quality controlled, flawless and certified canister components are delivered to the encapsulation facility. Therefore, quality assessment measures for the finished and closed canister only are discussed here. The main issue in this context is, obviously, the canister closure weld and the control of the weld process.

The first aspect for the control of the weld process is the monitoring of the weld process parameters. Before the encapsulation starts, the weld process parameters for acceptable welds have to be verified and certified, as described in Chapter 4. The monitored weld parameters must lie within the verified process window; welds made with parameters outside this window have to be rejected. For the electron beam welding used here, process parameters that need to be monitored are, for example, the vacuum inside the welding chamber, the power input and temperature of the electron source, power input of the inductor for the beam’s bundling, the bundling and the focusing of the beam, the position and velocity of the canister turning device and the contact pressure between canister hull and lid. Monitoring the process parameters is also an important component of SKB’s approach to guarantee the quality of the KBS-3 canister (SKB, 2010).

The next step would be the inspection of the finished canisters. Only non-destructive testing methods are usable here. First, the canister will be inspected by the use of ultrasonic methods to detect defects in the weld and heat-affected zone. The possibilities and use of this technology were already described in Chapter 4. Use of ultrasonic testing is also intended by SKB (SKB, 2010) and Andra (Andra, 2016).

Additionally, the canister surface should be checked. By using a swab test, the canister can be checked for contamination. If the canister is contaminated, it needs to be decontaminated and the origin of the contamination should be searched for. Furthermore, the radiation dose on the canister surface should be controlled to guarantee the compliance with threshold values. Optical inspection of the canister surface is also done to ensure the canister has not undergone any damage that could affect its function in the repository or could prevent further handling, such as deformations or scratches. As the last step, the canister weight should be controlled to ensure that the canister is filled with the designated amount of waste.

7 CONCLUSIONS AND RECOMMENDATIONS

Due to the small amount of high-level waste in Norway, deep borehole disposal is a possible alternative to a mined repository. With this concept, a deep borehole is drilled into crystalline rocks from the ground surface. After completion of waste disposal in the lower section, the upper section of the borehole is sealed with a long-term barrier system. The safety case for such a concept would place great emphasis on the great depth of burial, which shall ensure that the waste remains isolated from the accessible environment. The isolation function of the natural barrier is supported by engineered barriers such as the canister and the borehole sealing. This report described the development of a preliminary canister design for deep borehole disposal.

The work followed the idea to design a simple but robust canister that in combination with the other barriers can provide isolation as well as containment over the required time. The canister itself must not provide all the safety functions during the full time. The six major safety functions of the canister are containment, radiation shielding, sub-criticality, limiting temperature, limiting corrosion and operability.

Radiation shielding and operability are relevant for the operational period up to the disposal and closure of the repository. The designed DBD canister is not sufficiently shielded by itself. The steel mantle provides only a certain shielding. To meet the regulatory requirements in regard to the actual radiation level an additional transport cask is needed. Additionally, the transport cask gives mechanical protection to the canister during transport.

The four other safety functions – containment, sub-criticality, limiting temperature and limiting corrosion – are more relevant during post-closure evolution. In the preliminary canister design presented in this report, the duration was chosen to be the duration of significant thermal input from the waste. A clear definition of this thermal impact is connected to some uncertainty. On the one hand, the near-field EBS design, the known (thermal) properties of the host rock and decay heat power of the SNF or vitrified waste provide a good base for the prediction of temperature evolution. Thermal properties of rocks and various rock types are reasonably well known, and there are lots of temperature and thermal gradient measurements available. Sensible estimations even for the DBD depths can be made.

A clear regulatory requirement for the duration of containment does not exist. Duration shall be such that no harm is caused. One way to estimate the containment duration is a post-closure safety assessment showing that regulatory limits of annual doses or activity releases per annum are fulfilled, even with a breached canister. Post-closure safety assessment was outside of scope of the current work.

The absence of an actual site is relevant for the evaluation of corrosion. The designed canister follows the approach to limit the containment function to a not yet defined duration. Wall thickness, type of shell material (outer steel shell) and geochemical environment can allow a prediction of the corrosion rate. The resulting canister lifetime and containment function within the given boundary conditions is then defined by the mechanical stability. The expected planar corrosion rate of the considered stainless steels promises a very long duration of more than 1,000 and up to 10,000 years. On the other hand, the risk of local corrosion, e.g. pitting corrosion, is present and could limit containment leading to a release of nuclides. The estimation of local corrosion is strongly linked to the geochemical conditions. Available laboratory tests show that especially in brines with high chloride content the corrosion resistance of stainless steel is significantly reduced. The usability is then marked with a question mark or even not given. In the current design, two different material options are given. If the austenitic steel is not suitable, a DUPLEX steel can be used as well. A final evaluation requires a better knowledge about the actual site conditions. Favourable site conditions are represented by a low microbiological activity, low salinity, low chloride and oxygen content of the formation water, low Eh value and a pH value of at least 8.

The designed canister consists of an outer shell made of stainless steel and an insert to cover the different SNF elements. One outer shell design was proposed. For different types of waste, several inserts can be designed. The number of assemblies can be limited by thermal aspects or sub-criticality. The designed borehole canister can be used without an insert for reprocessed waste, such as CSD-V canisters. The single canister design simplifies the canister manufacturing and the complexity of the encapsulation facility.

The canister design, as described in this report, represents a first draft version of a DBD canister and follows the idea to provide a simple and robust design. As highlighted several times, the design is connected to a high level of uncertainty, which results from the early stage of the programme and the absence of detailed data of deep geological conditions at the actual site. However, options to adapt the design to properties varying for the current assumptions were named. A further optimisation of the design can be done with increasing knowledge.

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