# Deep Borehole Canister Development for Norwegian High-Level Radioactive Waste – Paper 23223

Philipp Herold *, Ansgar Wunderlich*, and Toivo Wanne*
*BGE TECHNOLOGY GmbH, Peine, Germany

## ABSTRACT

Norwegian Nuclear Decommissioning (NND) is currently actively running a radioactive waste management programme and developing disposal concepts for all radioactive waste types existing in Norway. The 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 radioactive waste (LILW) from the planned decommissioning of the research reactors and other nuclear facilities. NND is developing a comprehensive strategy for management of all these waste types. The currently planned options for the disposal are:

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

Of the disposal options for HLW the deep borehole disposal concept is generally on a lower maturity level compared with the DGR option. NND is therefore running projects that will bring the DBD type repository to a more equal level with the DGR, before they will make the final decision on which disposal concept will be realised in Norway. This paper presents newly developed information on the deep borehole disposal canister for crystalline host rock and, therefore, brings the concept to a more mature level.

This paper provides basic information about the deep borehole disposal canister design. First, the safety functions of the canister in deep borehole disposal are described. In the work the safety functions and requirements for the canister are quantified.

The safety requirements are subsequently used to prepare the canister concept design for deep borehole disposal in crystalline host rock in Norway. In addition, the manufacturing process of the canister is described. The material chosen for the canister manufacturing is discussed, including the dimensioning of the canister.

Furthermore, the geochemical environment and corrosion processes are described to predict the long-term performance of the canister. The work also discusses the required encapsulation process for the canister designed. This is how the high-level waste is encapsulated in the canister, including the hot cell, welding, and inspection requirements.

## INTRODUCTION

Norwegian Nuclear Decommissioning (NND) has been working with Finnish AINS Group, Mitta Oy together with VTT Technical Research Centre of Finland and BGE TECHNOLOGY GmbH of Germany. The group has assisted NND since January 2020 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 e.g. by the medical sector. NND is developing a comprehensive strategy for managing 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 disposal for high-level waste,
- Landfill-type repository for non-radioactive decommissioning waste.

The repository types are presented in the report "Concept Description for Norwegian National Disposal Facility for Radioactive waste" [1]. The report includes concise concept descriptions of the possible disposal options. The borehole disposal concept was further developed in [2], [3], and [4]. Encapsulation processes for HLW, both for DGR and DBD concepts, were described in [5].

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

The aim of this work is to generate the first concept version of a deep borehole disposal canister for the disposal of high-level radioactive waste in Norway. First, there is a description of the safety functions of a canister in the borehole concept. After that, the safety functions, such as the minimum 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, lengths 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. Subsequently, the emplacement of waste in the canister is described for a generic waste package.

The paper finishes with the description of the working steps for canister production and encapsulation. Also, there is a description of the necessary technical requirements of an encapsulation plant.

## DEEP BOREHOLE DISPOSAL FACILITY FOR NORWAY

The deep borehole disposal concept for Norway is described in [2] 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, a deep borehole is drilled into crystalline rock 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 emplacement, which shall ensure that the waste remains isolated from the accessible environment.

Crystalline rock formations are widespread and offer advantageous conditions for deep borehole disposal in Norway. The geology of Norway is characterised by crystalline rock formations 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 geologic 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.

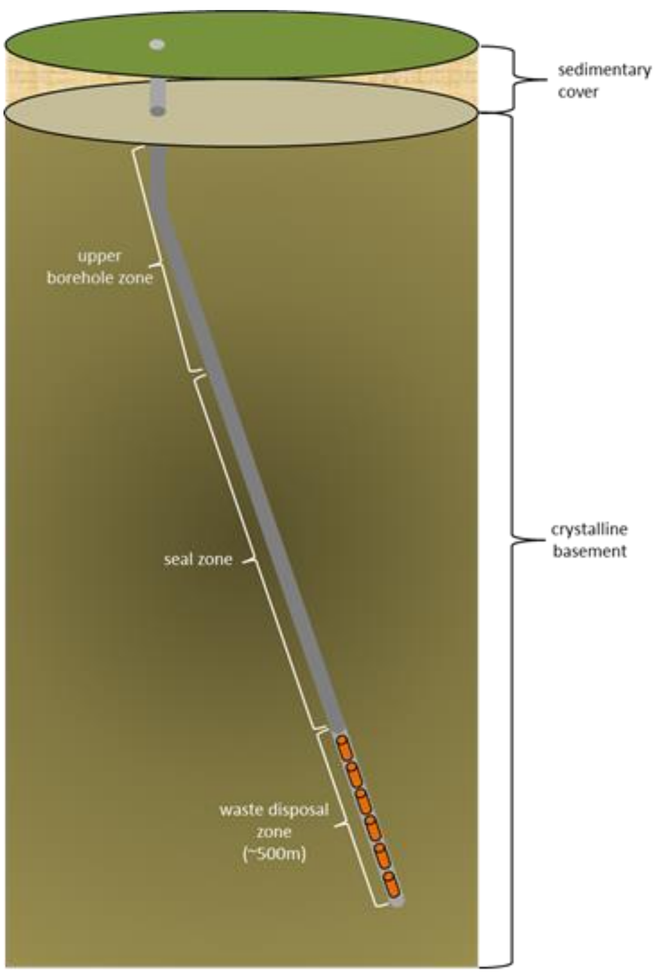


*Figure 1: Schematic view of the borehole disposal, based on [2].*

## SETTING THE BASIS FOR THE DISPOSAL CANISTER DESIGN

### Requirements and safety functions for disposal canister

Host rock target properties analysis [6] for the generic disposal site gives a systematic approach to developing 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.

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:

Target properties [6] 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 German team of experts [7] developed a method for determining the safety functions of a disposal canister. The requirements and the functions for repository canisters were derived using a top-down approach. Adapted to the Norwegian DBD concept, 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. The safety functions are summarised in Table 1.

*Table 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 |

## Processes affecting the disposal 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 the 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 impacts can be influenced by the inventory put in one canister. Chemical and/or biological impacts result mainly from liquids and their (aggressive) compositions. The presence and compositions of liquids are determined by the environment. Table 2 summarises the impacts and safety functions.

*Table 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<br>End defined by corrosion effects and 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<br>Near-field materials and design<br>Rock temperature |
| **Limiting corrosion** | | Liquids present (amounts and compositions) |
| **Operability** | Dynamic and static mechanical impacts | |

## QUANTIFICATION OF CANISTER SAFETY FUNCTIONS

### 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 may 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.

To estimate the required canister lifetime, the thermal properties of the spent fuel and possible waste from reprocessing can be used. The necessary canister lifetime is the time of the waste's heat production. During this time, the canister has to provide containment. The thermal output of different fuel types have been analysed and according to this, the canister has to provide containment for up to 5000 years, which needs to be considered in the canister design and material selection.

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. The second indicator is stability. A canister for borehole disposal is a thin-walled structure and, therefore, may fail through buckling. Buckling is the sudden change in shape of a structural component under load. The canister design must prevent buckling due to axial stresses. The third indicator is deformation resistance. The plastic deformation must be below the deformation limit of the canister material.

The last indicator is long-term durability. The canister will be affected by corrosion and has to be leak-proof for at least 5000 years. Therefore, the canister must be sufficiently resistant against corrosion for this period, and its wall thickness must be large enough.

### 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” [8]. 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.

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.

Sub-criticality has to be ensured for the most reactive configuration with optimum moderation and close reflection [9]. 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.

### 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.

The temperature inside the canister has to be limited as well. The temperature limit for fuel assemblies or rods with Zircaloy cladding is usually set to 400 °C. The reason for the temperature limit is to protect the cladding and to maintain its barrier function against release of radionuclides. Additionally, Norway has fuel assemblies and rods with aluminium cladding. For aluminium-clad fuel, the temperature criteria are set to 200 °C. In an alternative Norwegian concept, it is intended to process the fuel rods with aluminium cladding and to put the fuel into stainless steel tubes. The temperature limit for stainless steel has been set to 330 °C.

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’s outer surface. The purpose of the outer canister surface temperature limit in mined repository concepts (DGRs) is protection of other barriers in the direct vicinity of the canister, usually the host rock and the sealing (buffer) system. For deep borehole disposal, the approach is different. In deep borehole disposal, the disposal depths used are greater than in mined repositories. The disposal zone in the deep borehole disposal concept can be expected to be at around 1500 metres to 3500 metres depth. The natural rock temperature at this depth is usually higher than in mined geological repositories (DGRs). At 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.

Another aspect is the protection of the sealing system. Seals made of bentonite usually need to be protected against temperatures above 100 °C, which is one of the reasons a temperature limit of 100 °C is usually applied to crystalline rock for DGRs. 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. In the deep borehole disposal concept, the sealing zone is usually placed several hundred metres above the disposal zone, and no bentonite seals are located directly adjacent to the canisters. Therefore, a strict temperature limit for the canister is not necessary in for the Norwegian deep borehole disposal concept.

### Limiting corrosion

It is necessary to limit corrosion and gas production by the canister materials. The canister must be leak-proof for at least 5000 years, and high gas pressure, which can affect other barriers such as the sealing system or the host rock, needs to be prevented. Corrosion is controlled by choosing a canister material that suits the geochemical environment in the borehole disposal site.

## CANISTER DESIGN

The canister is designed to contain all potential waste types. Thus, its dimensions are defined by the maximum lengths and diameters of the different spent nuclear fuel 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 distribution over the inner surface.

The canisters are exposed to high weight loads 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. Figures 2 and 3 respectively show the canister outside and with CSDs inside it.

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

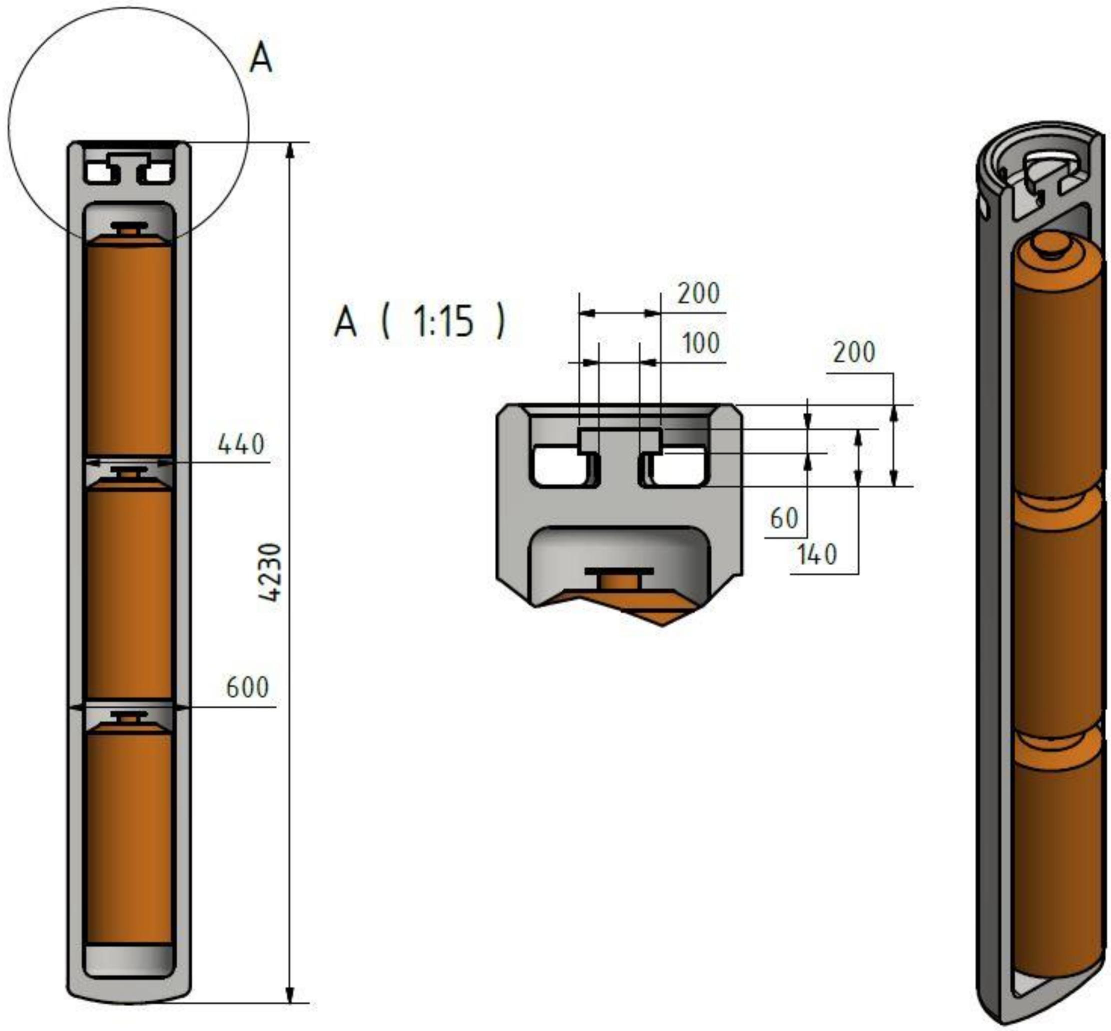


Figure 3: Half cut of the canister loaded with three CSD-V casks and including dimensions.

## CANISTER MANUFACTURING

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 production and before the canister is brought to the radioactive waste handling room. The top cover is welded in the hot cell after the canister has been filled.

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 carried out after the electron beam welding is done. 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.

In the following, the main manufacturing steps are described. The steps are shown in Figure 4.

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 their 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 forging, additional samples have to be taken to test if the material properties conform with the specifications of 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 to the hull by either electron beam welding or other welding techniques, such as metal inert gas welding. After welding, the weld should be machined and treated. Additionally, non-destructive testing is necessary to detect defects in the canister hull and the weld. For the testing of the weld, non-destructive testing such as ultrasonic inspection or X-ray inspection can be used. 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 be performed in the hot cell using the available electron beam welding equipment.

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.

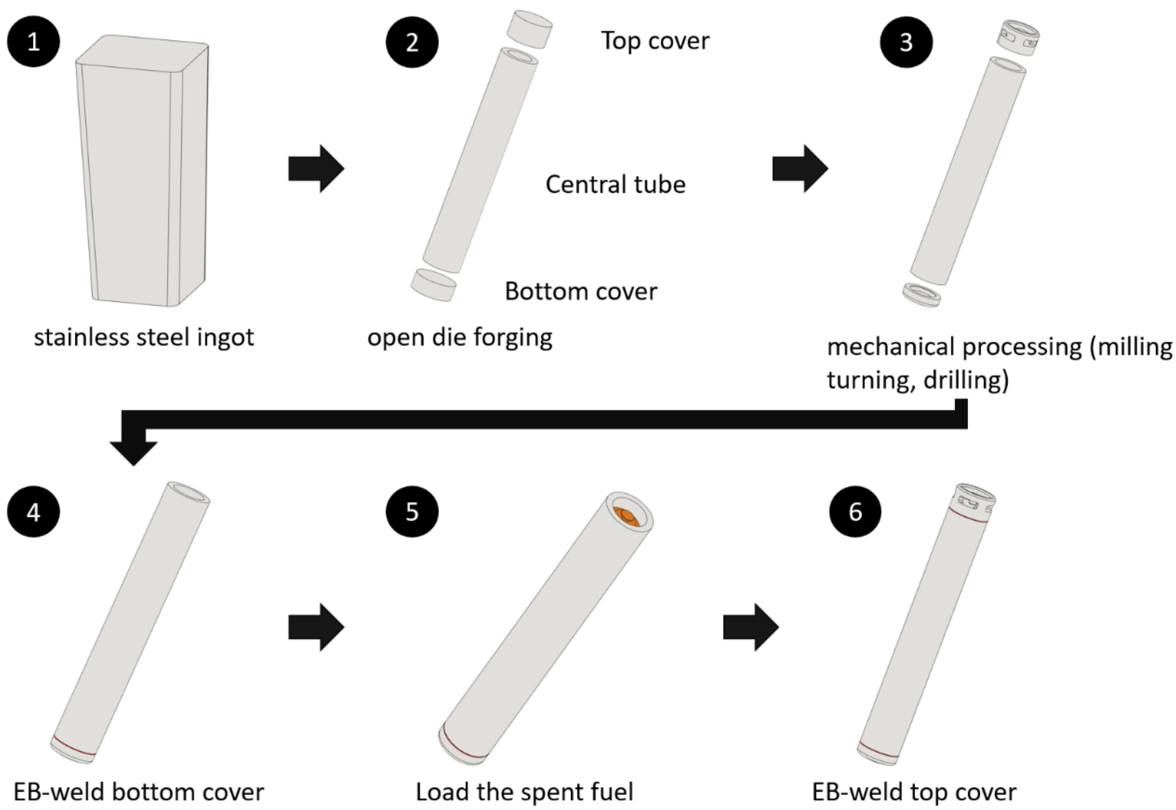


Figure 4: Illustration of the main steps during canister production and encapsulation.

**ENCAPSULAITON OF FUEL IN THE CANISTER**

Before encapsulation, some of the Norwegian spent nuclear fuel need pre-treatment to be acceptable for the process. Consequently, the spent nuclear fuel should meet at least the following criteria:

- The fuel bundles/rods are intact.
- The fuel bundles/rods are in airtight condition so that no contamination by volatile radionuclides would occur.
- The fuel bundles/rods are handleable so that the lifting and transfer operations in the fuel handling cell are possible.

Drying of the wet fuel bundles is not considered necessary in Norway, where the amounts of spent fuel and number of disposal canisters are small. Therefore, it can be assumed that the corrosion caused by wet fuel bundles does not constitute a risk that would not fit within the safety margins of the concept. The generic encapsulation process for the DBD canister is described in [3]. It is planned in the following steps:

1. Acceptance of spent nuclear fuel and canister components
2. Transfer to the fuel handling cell

3. Unloading of the spent fuel transport cask
4. Loading of canister
5. Canister closure by electron beam welding
6. Canister test, test for contamination and decontamination

After encapsulation, the canister is transported to the deep borehole disposal rig, suggesting that a canister lift is not needed. Considering the small number of canisters to be disposed of (about 90 canisters for Deep Borehole Disposal), no buffer storage nor related transfer operations and systems for packed canisters would be needed. A canister filled with spent fuel would be transported directly to the disposal facility and not stored in the encapsulation plant or elsewhere while waiting for disposal

## CONCLUSIONS

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 rock 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 emplacement, 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 seal.

The work followed the idea of designing 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 entire time. The six major safety functions of the canister are containment, radiation shielding, sub-criticality, limiting temperature, limiting corrosion, and operability.

The canister designed 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 may be limited due to thermal aspects or sub-criticality. The borehole canister designed can be used without an insert for reprocessed waste, such as CSD-V canisters. The single canister design simplifies canister manufacturing and the complexity of the encapsulation facility.

The canister design, as described in this paper, represents a first draft version of a DBD canister and follows the idea of providing 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 Norwegian radioactive waste management 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. The design can be optimised further with increasing information and knowledge.

## REFERENCES

[1] Ikonen, A., Engelhardt, J., Fischer, T., Gardemeister, A., Karvonen, S., Keto, P., Wanne, T. (2020). Concept Description for Norwegian National Disposal Facility for Radioactive Waste. AINS Group.

[2] Fischer, T.; Engelhardt, J.; Wanne T. (2020) Deep Borehole Disposal Concept. Technical Report. Technical Assistance “National Facility”. Germany. September 2020.

[3] Wunderlich, A., Seidel, D., Herold, P., Wanne, T. 2021. Deep Borehole Disposal Canister. Germany. AINS Group.

[4] Engelhardt, H-J, Fischer, T. & Wanne, T. 2021. Sealing of Deep Boreholes in Crystalline Rock. Norwegian National Facility. AINS Group Technical Report. BGE TEC Germany. September 2021.

[5] Saanio, T.; Seppälä, T; Gardemeister, A; Wunderlich, A.; Herold, P, & Wanne, T. (2022) Encapsulation of HLW Canisters – Norwegian National Disposal Facility for Radioactive Waste. Technical Report. Technical Assistance “National Facility”. Finland Germany, January, 2022.

[6] Hagros, A., Engelhardt, J., Fischer, T., Gharbieh, H., Häkkinen, I., Ikonen, A., Ärväs-Tuovinen, T. (2021). Host Rock Target Properties for Norwegian National Facility for Radioactive Waste - Draft version. AINS - Civil Engineering.

[7] Bollingerfehr, W., Prignitz, S., Wunderlich, A., Herold, C., Perez, T. O., Völzke, H., & Wolff, D. (2020). Anforderungen und Konzepte für Behälter zur Endlagerung von Wärme entwickelnden radioaktiven Abfällen und ausgedienten Brennelementen in Steinsalz, Tonstein und Kristallingestein. Peine. BGE TECHNOLOGY GmbH.

[8] Loukusa, H., & Nordman, H. (2020). Feasibility of KBS-3 spent fuel disposal concept for Norwegian spent fuel. Espoo: AINS GROUP.

[9] Raiko, H. (2012). Canister Design 2012. Olkiluoto: Posiva Oy.