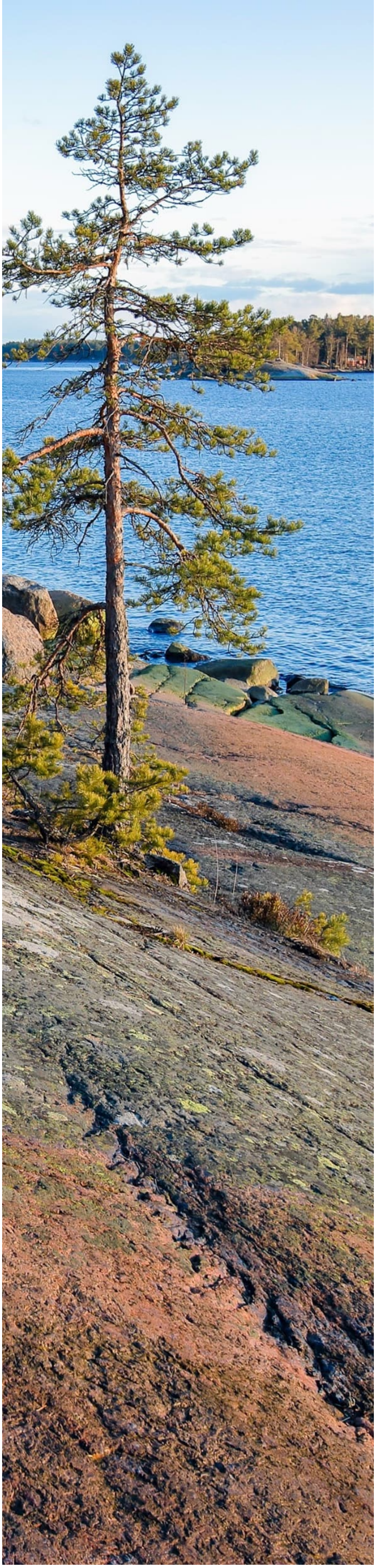

Technical Memorandum

Encapsulation of HLW Canisters – Norwegian National Facility

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ABSTRACT

Norwegian Nuclear Decommissioning (NND) is developing disposal concepts for the Norwegian spent nuclear fuel inventory. Two geological disposal concepts are considered: a KBS-3 type DGR and deep borehole disposal (DBD). In the concepts, waste canisters are placed in deep geological formations. The two concepts differ, for example, in their requirements for the canister (physical dimensions, manufacturing techniques, and waste encapsulation process).

This report analyses canister manufacturing and encapsulation processes between the two proposed canister types. Furthermore, these processes are streamlined to Norwegian conditions. The key objective was to study whether the feasibility, cost, and other strategic considerations differ between the two concepts to such an extent that it could inform a decision on one concept versus the other.

This study suggests that the encapsulation process for the DBD concept is simpler than for the KBS-3. The DBD canister has a single structure with no copper shell (overpack), and with electron beam welding, machining of the weld of the lid is not needed. Being lighter and smaller than the KBS-3 canister, it is suggested that the DBD canister can be operated in a “drive-through” transfer cask during encapsulation without the need of extra shielding between different stations of operation. As the size of the DBD encapsulation plant is also smaller than the KBS-3, the overall costs for the DBD encapsulation are smaller. However, most of the R&D for the KBS-3 concept has already been done as the disposal operations are planned to be started in Finland in a few years. In the future, the feasibility of the DBD concept should be studied in detail to provide more information of the costs related to R&D of the concept.

In addition to the encapsulation of spent nuclear fuel in Norway, international alternatives for encapsulation have been reviewed in the report. From the technical point of view, Finland and Sweden have the most advanced knowledge of the KBS-3 type encapsulation. Regarding the DBD canister, encapsulation technology has not been developed. Existing spent fuel reprocessing plants in Europe (e.g. La Hague and Sellafield) have technologies to operate with spent nuclear fuel but not for the encapsulation process without additional technology development at plants.

Keywords: Deep Borehole Disposal (DBD), Deep Geological Repository (DGR), KBS-3 concept, DBD canister, KBS-3 canister, manufacturing, encapsulation, generic design, cost assessment

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1 INTRODUCTION

1.1 Background

Norwegian Nuclear Decommissioning (NND) is working with the 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, e.g., by the 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. The borehole disposal concept was further developed in Fischer et al. (2020).

This report focuses on a high-level comparison of manufacturing of canisters, and encapsulation processes for spent nuclear fuel between the deep borehole (DBD) and KBS-3 canister types. The aim is to provide answers to whether the feasibility, cost, and other strategic considerations related to encapsulation are different for KBS-3 and DBD to such an extent that it could inform a decision on one versus the other. In addition, this report reviews the availability of international encapsulation services should spent nuclear fuel be encapsulated outside Norway.

1.2 HLW disposal concepts in Norway

Figure 1-1 depicts the National Facility with a KBS-3 type DGR and the alternative DBD concept.

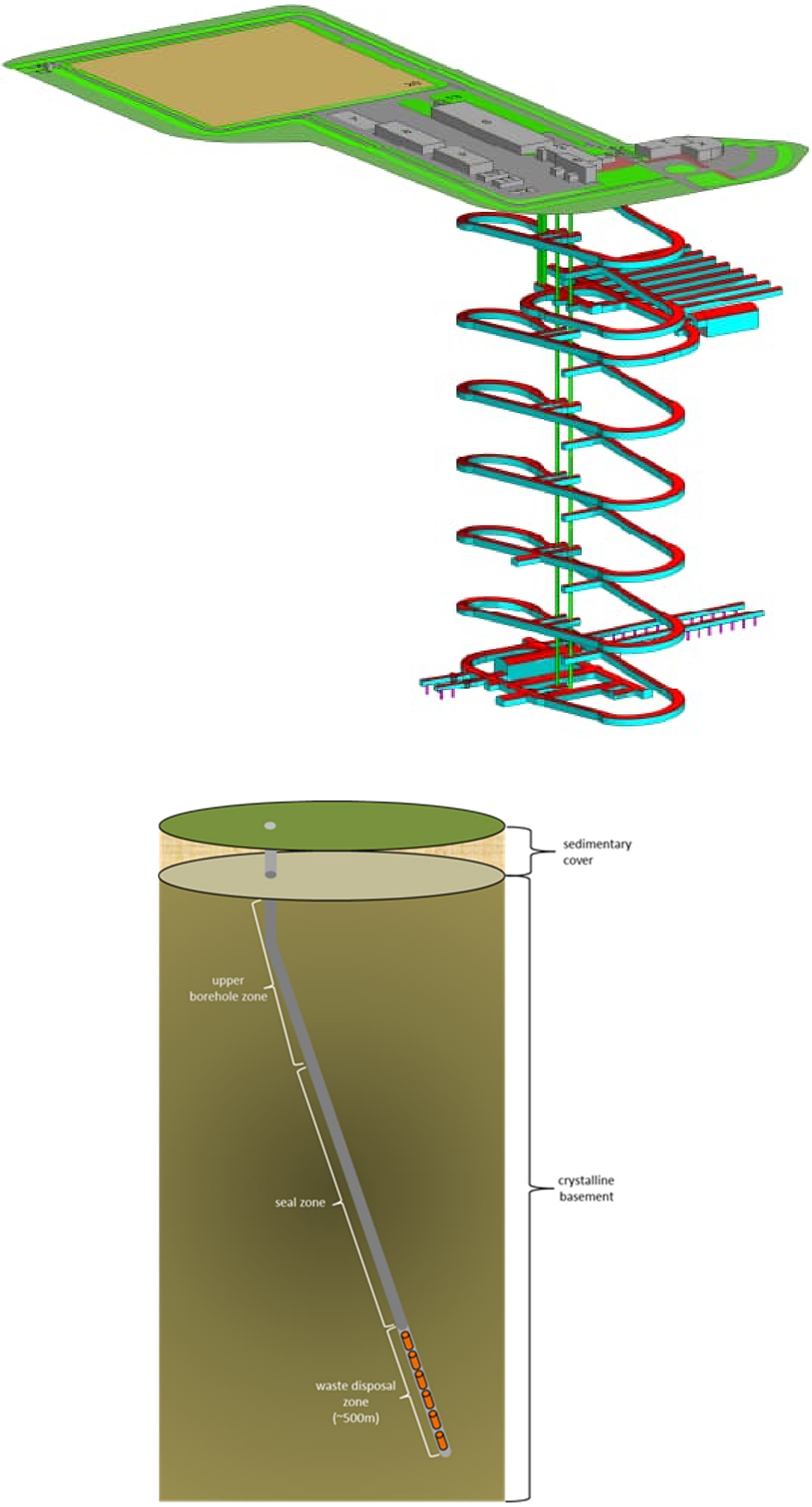


Figure 1-1: Illustration of the Norwegian National Facility (above) with surface and underground infrastructure with the option of a DGR for HLW disposal. Below – a schematic view of the borehole disposal concept, based on Ikonen et al. (2020).

1.3 Canisters considered in the work

1.3.1 KBS-3 canister

In Sweden and Finland, copper canisters are planned to be used for disposal of spent nuclear fuel using the KBS-3 method. Gas- and watertight canisters consist of two main components: a load bearing insert made of cast iron with channels for the spent fuel bundles and an outer corrosion resistant shell made of copper. The copper shell has a wall thickness of 50 mm. (Jonsson et al., 2018).

In addition to main components, the canister consists of an inner steel lid and welded copper lid. The base of the copper shell can be integrated with the shell, or the bottom lid can be welded.

The following figure shows sketches of the KBS-3 canister. The length of the canister and the design of the insert may vary depending on the encapsulated fuel; however, this has only a minor influence on the manufacturing processes.

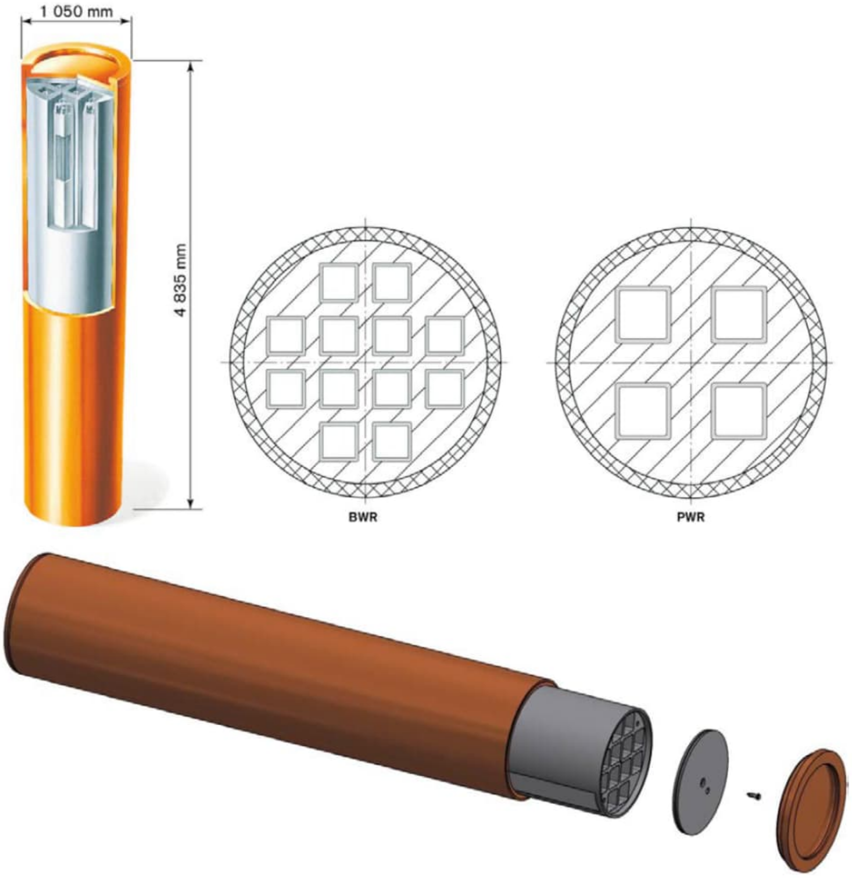


Figure 1-2: Upper left: Schematic of the general design of the KBS-3 canister showing the insert and the copper shell. Upper right: a cross section of inserts for boiling-water reactor (BWR) and pressurized-water reactor (PWR) spent fuel. Lower: A schematic view of the KBS-3 canister and its components. From left to right: copper tube with base, insert, steel lid for the insert, screw for the steel lid and copper lid. (Jonsson et al., 2018).

1.3.2 DBD-v1 canister

In the context of this work, the canister for the borehole disposal concept was developed in Wunderlich et al. (2021). This canister is referred to as the “DBD-v1 canister”.

The DBD-v1 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 CSDV (Colis Standard de Déchets Vitrifiés, Standard Container for Vitrified Waste) 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 3700 mm. The overall length of the canister is 4230 mm. The canister is made of stainless steel, either using an austenitic steel or DUPLEX steel. The canister itself is load bearing and is planned to withstand corrosion for 5000 years. The canister is designed as a single shell for the disposal of canisters with vitrified waste from reprocessing. For the use with fuel rods or elements different inserts for the different types of spent fuel are envisaged but have not been designed yet. The canister shall be disposed in deep vertical boreholes with a depth of around 3000 m. Figure 1-3 shows the DBD-v1 canister.

Figure 1-3: DBD-v1 canister for deep borehole disposal (Wunderlich et al. 2021).

2 CANISTER MANUFACTURING PROCESSES

2.1 Introduction

In this chapter, the process for canister manufacturing is described for both the KBS-3 and the DBD-v1 canisters.

2.2 Manufacturing of the KBS-3 canister

The manufacturing of the KBS-3 canister is described in SKB's Technical Report "Design, production and initial state of the canister" (SKB 2010. The following flow chart is taken directly from that report and shows the steps from canister manufacturing to disposal. Highlighted in the red square are the steps that are described further in this report. There are also multiple reports for details of the canister manufacturing, such as manufacturing of insert or copper tubes, welding or different testing options written either by SKB in Sweden or Posiva Oy in Finland. Multiple prototypes of the KBS-3 canister have also been produced.

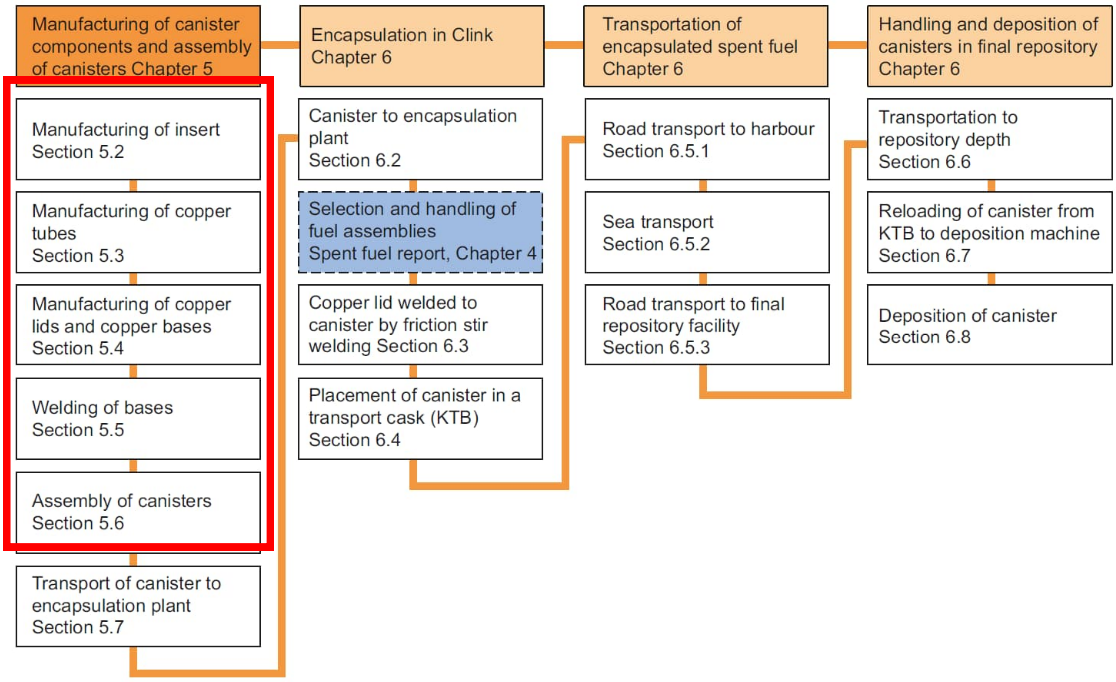


Figure 2-1: Flow chart for all stages concerning the canister in the KBS-3 concept. The included references are referring to the sections of SKB TR-10-14. Highlighted with the red square are the further described steps in this report. (Taken from SKB 2010.)

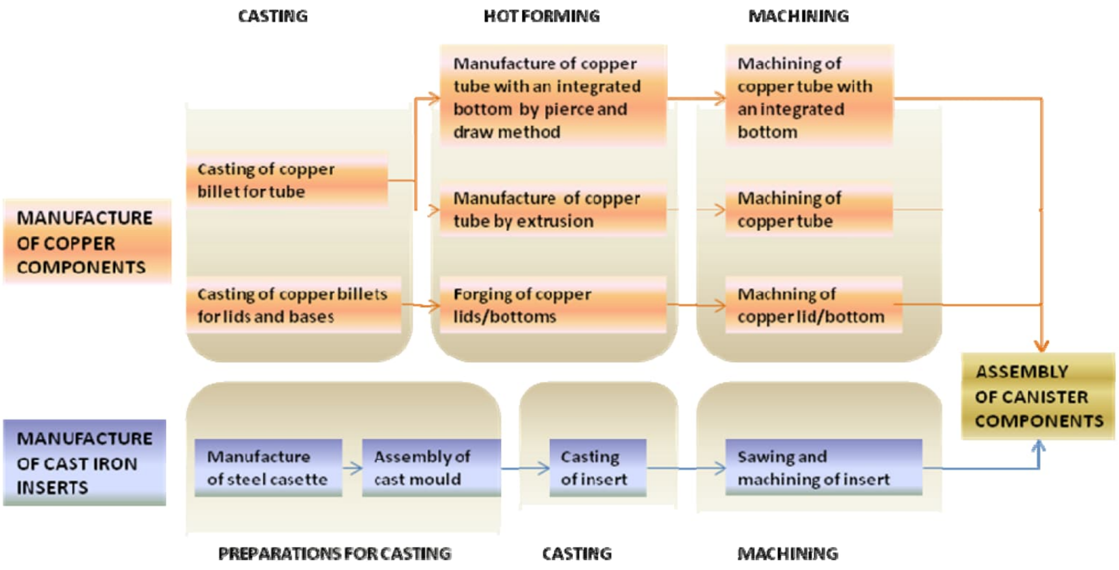


Figure 2-2: Flow chart for the manufacturing of KBS-3 type disposal canisters (Raiko et al. 2012).

2.2.1 Manufacturing of the insert

The insert of the KBS-3 canister consists of a steel tube cassette, the insert itself and a steel lid.

Manufacturing of the steel tube cassette

The first step in the manufacturing of the insert is the assembly of the steel tube cassette. The steel tube cassette is manufactured from standardised square steel tubing. This is welded together with support plates to form the steel tube cassette. (Raiko, 2005). During the manufacturing of the steel tube cassette, attention is focused on the straightness of the steel tubes. This is necessary to guarantee a later unproblematic insert of the spent fuel elements. The straightness of the steel tubes is controlled with a gauge before and after welding. Before placing in the casting mould the steel tube cassette is bathed in hydrochloric acid or sand blasted to remove rust (Raiko, 2005). Figure 2-3 shows the finished steel tube cassette.

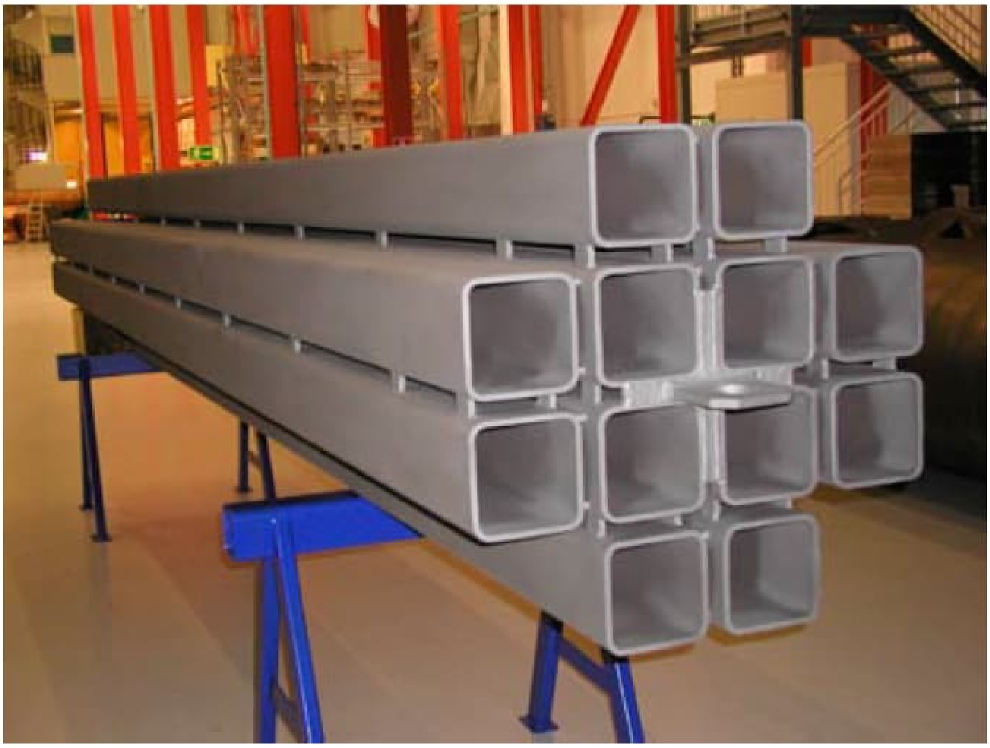


Figure 2-3: Steel tube cassette after manufacturing (SKB, 2010).

Casting of the insert

For the casting of the insert, the steel tube cassette is placed inside the mould. The formwork and method of casting can vary between different foundries. In the test production of canister inserts, both sand and steel moulds have been used. The filling of the mould can happen either from the top of the mould or from its bottom, whereby the molten metal is led via a channel inside the mould. Before casting, the steel tubes in the cassette are filled with sand which is compacted. This prevents deformation of the steel tubes during casting. For the casting, molten iron with temperatures around 1310 and 1370°C are used. The filling of the mould takes around one minute. After casting, the mould is left for cooling for several days. The insert is always cast with a surplus length in order to be able to cut away a certain section at the top where slag and other impurities gather.

Before and during the casting, process parameters such as chemical composition, cast iron treatment, temperature and slagging are continuously monitored. After the cast insert is knocked out of the mould, the insert is cleaned and the surplus at the top is cut and finished. Also the eccentricity of the cassette is measured to make sure it conforms to the specified value. Later the insert is pre-machined on its exterior and the sand in the cassette is removed. After pre-machining, the insert is inspected by non-destructive testing. For the insert, ultrasonic testing is used. If the insert conforms with the requirements, it is machined to its final dimension and surface roughness. During the casting also samples for destructive testing of the material properties are either cast on or are produced from the excess that is cut. Figure 2-4 shows the finished cast iron insert.

Prior to May 2008, a total of 55 test inserts were produced. Further information of the experiences gained during the test castings can be found, for example in Raiko (2003 and 2005).

Figure 2-4: Machined insert for BWR spent fuel (Raiko, 2003)

Manufacturing of the insert lid

The lid for the insert is made of 50 mm steel plate. The lids will be delivered ready machined to their dimensions and with the hole for the screw and valve to the canister factory. The lids also have a furrow at their outside to fit a gasket in.

2.2.2 Manufacturing of the copper shell

The outer copper shell of the KBS-3 canister is made out of cast copper ingots which are later finished into copper tubes. In addition, the base and the lid for the copper tube must be manufactured.

Casting of copper ingots for tubes

The copper ingots are casted with a diameter of 850 mm by semi-continuous casting of oxygen-free copper. The casting starts with the melting of preheated cathodes in a melting furnace. When the target temperature is reached, the melt is poured via a launder into a holding furnace. Then the melt is, in a reducing atmosphere, poured into a mould via a casting tube. Phosphorous is fed into the meld in the launder. The mould is a water-cooled matrix with a diameter of 850 mm, where the solidification starts. Casting occurs in a semi-continuous process. The whole ingot is cast downwards into an inclined casting pit.

The ingot itself weighs around 16 tons after casting. This is also the maximum weight possible for an ingot casted at the suppliers of SKB or Posiva. The ingot is casted with some excess which is cut and machined afterwards. The excess is necessary because central cracks occur at the top end of the ingot when solidification begins. Those can be cut away with the excess material. The ingot is also machined to a final diameter of about 830 mm. The end weight and length of the ingot depends on the following production method. Ingots for tube manufacturing by pierce and draw method weigh about 13.4 tons, ingots for forging or extrusion weight about 12.4 tons.

During the casting process the process parameters are constantly monitored. Also samples for the monitoring of the chemical composition are taken. The ingot is also examined by dye penetration inspection to find cracks. (Nolvi,2009)

Figure 2-5: Large copper ingot for the production of copper tubes (SKB, 2010)

Manufacturing of copper tubes

For production of copper tubes for the KBS-3 canister, three different manufacturing methods were considered: Pierce and draw method, extrusion and forging. All three methods are hot forming methods which produce seamless copper tubes for disposal canisters. The pierce and draw method has the advantage that the canister base is integrated and does not require welding. The other methods are only capable of producing a copper tube without the base. SKB's reference method for producing the copper tubes is extrusion, which Posiva has also studied. Forging has the disadvantage that it is harder to control the achieved geometry.

For the pierce and draw method, the copper ingot is heated up at first. In Figure 2-6, the steps for upsetting and piercing are shown schematically. The heated ingot is upset with one stroke to a die and then it is pierced with a mandrel. The mandrel is not punched through; a bottom of 200 to 300 mm is left.

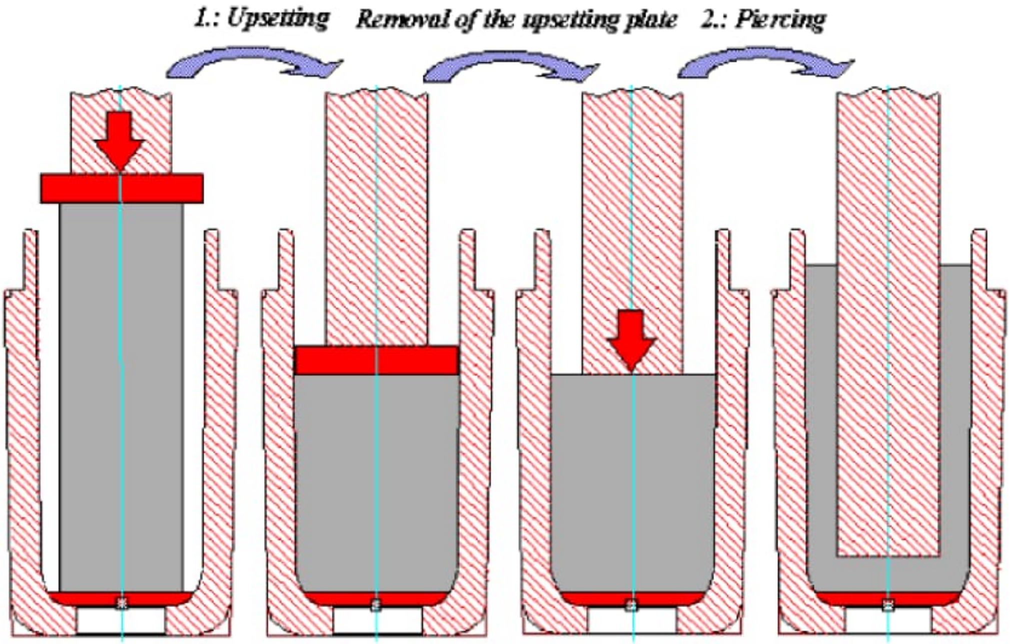


Figure 2-6: Phases of upsetting and piercing (Nolvi, 2009).

After the piercing, the expanding and drawing starts. This is done in multiple steps and the ingot is reheated again if it is cooled down to too low temperatures. The drawing steps are continued until the desired tube wall thickness is achieved. Finally, the bottom is formed using special tools. The expanding of the inner diameter is done by pressing a mandrel with a diameter larger than the inner diameter of the tube into the tube and pressing it against a steel plate. After that, the ingot is pushed through a drawing ring to form the outer contour.

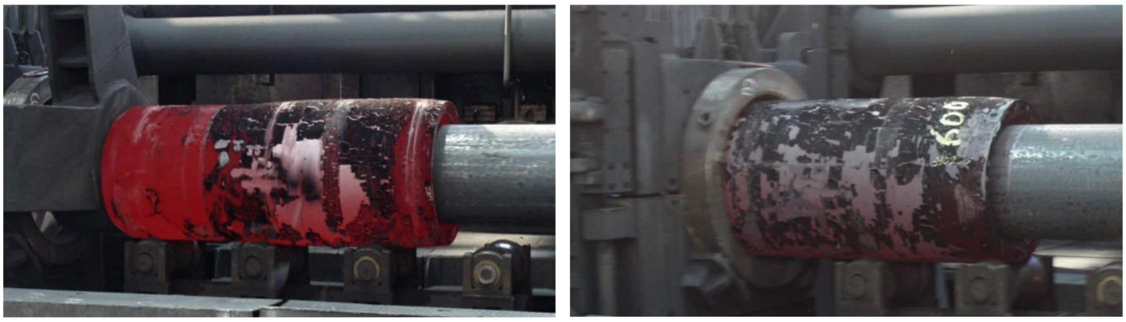


Figure 2-7: The left picture shows the expanding of the tube by pressing the tube with the mandrel against a steel plate, and the right picture shows the drawing pass (Nolvi, 2009).

Another possibility to manufacture the copper tube is by extrusion. The extrusion process consists of two separate steps. At first, the ingot is upset and pierced similar to the aforementioned pierce and draw method. After that, the tube is extruded.

The process is started by heating the ingot inside a furnace. Then it is upset to increase its diameter and pierced with a mandrel. The mandrel is centrally and vertically pressed through the billet and creates hole inside the ingot. After piercing, the ingot is machined and the centralisation is checked. Machining is necessary to get a totally symmetric tube form for the extrusion. The part described here is shown on the left side of the following figure.

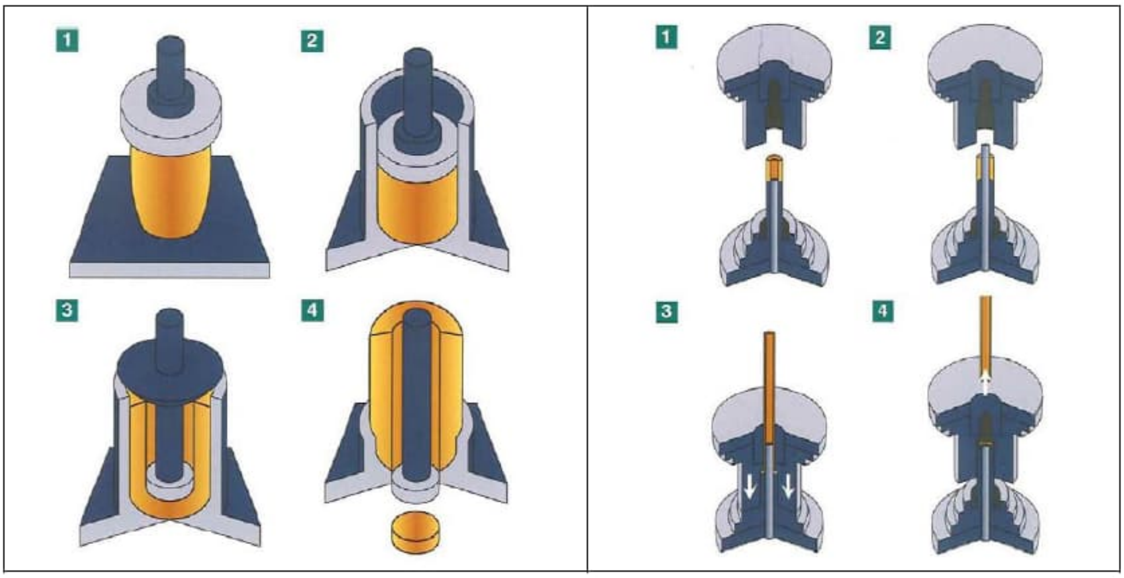
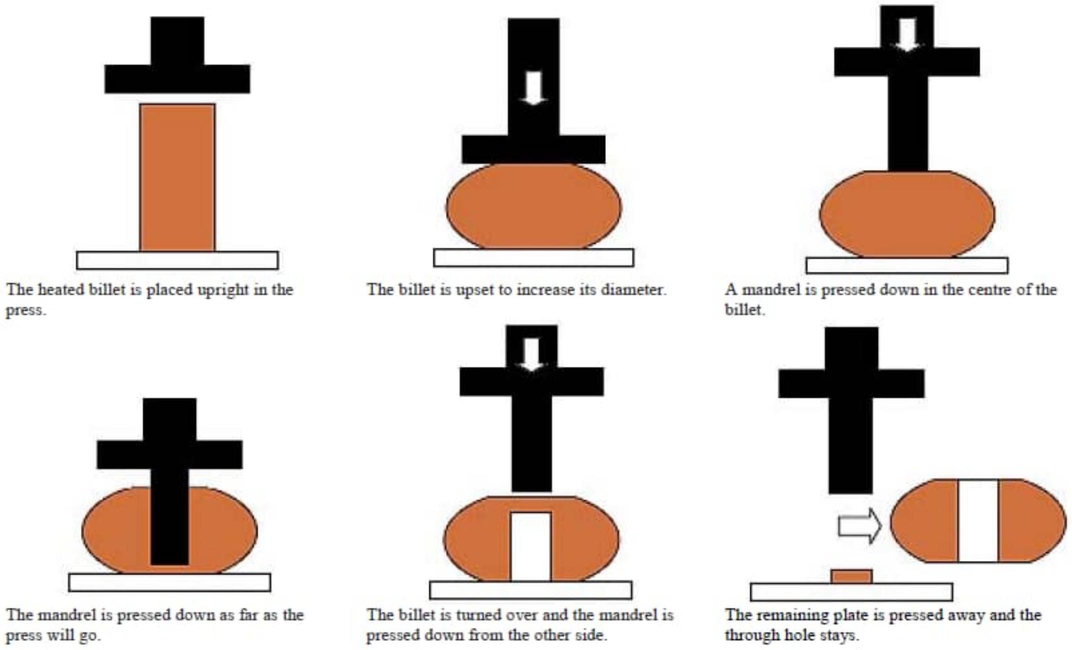


Figure 2-8: Upsetting (1), blocking (2), piercing (3) and trimming (4) of an ingot shown on the left, and on the right, the principle for the extrusion of the block is shown (Nolvi, 2009).

The extrusion is started with heating the blocker. Then the blocker is placed into an extrusion container which is pressed down over the blocker, as shown on the right side of Figure 2-8. As the container has contact with the blocker, the copper starts to extrude through the die. The extrusion continues until the full length of the tube has been extruded.

The third possible manufacturing method for the copper tubes is forging. The forging process consists of several steps. At first, the copper ingot is heated and upset to increase its diameter then the ingot is pierced using a mandrel with a diameter of 550 mm, Figure 2-9. After the piercing the hammer forging of the ingot starts. At first the inner diameter is increased until a mandrel with a diameter of 930 mm fits in. After that, hammer forging is carried out by turning and moving the mandrel axially until a long tube with uniform wall thickness is formed. The process of manufacturing large copper tubes by forging is schematically shown in Figure 2-10.



The heated billet is placed upright in the press.

The billet is upset to increase its diameter.

A mandrel is pressed down in the centre of the billet.

The mandrel is pressed down as far as the press will go.

The billet is turned over and the mandrel is pressed down from the other side.

The remaining plate is pressed away and the through hole stays.

Figure 2-9: Process steps for upsetting and piercing of a copper ingot (Nolvi, 2009).

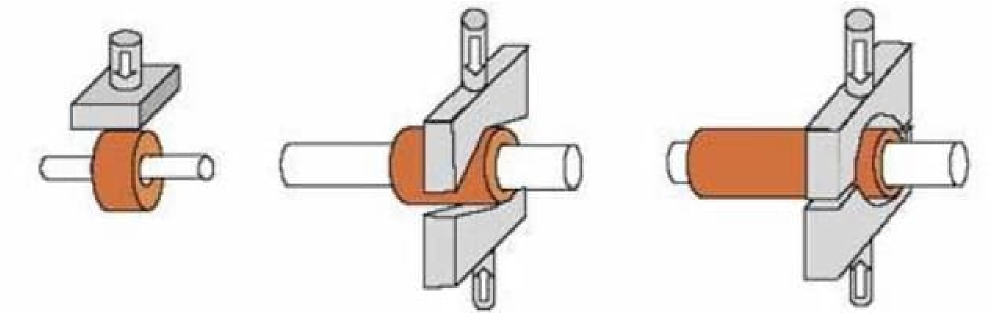


Figure 2-10: Steps in forging a copper tube: Hammer forging and forging with a mandrel (Nolvi, 2009.)

Independent of the manufacturing process all copper tubes are machined to the required measures and surface roughness after the hot forming. Dimensions and the geometry are verified. The tubes are examined with non-destructive testing, such as ultrasonic testing. Material properties are also examined using samples cut from excess material.

In Posiva's report (Nolvi, 2009) it is stated that up to the end of 2009 a total of 57 copper tubes have been manufactured: 17 tubes by pierce and draw method, 30 tubes by extrusion and 10 tubes by forging. SKB states in the report (SKB, 2010) that "in the past ten years" some 40 large copper ingots were cast and 27 copper tubes were produced by extrusion. The test manufacturing of two copper tubes for KBS-3 canisters is further described in Raiko (2008).

Manufacturing of copper base and lid

With the pierce and draw method, the copper base is integrated with the copper shell during the manufacturing process. Otherwise, the copper base and the lid are manufactured by forging. The manufacturing starts in the same way as the manufacturing of the tube by casting of an ingot but in a smaller size compared with the ingot for the copper tube. The description for this step can be taken from the manufacturing of the copper tubes.

For the forging, the ingot is heated in a furnace and then forged into the desired measures and geometry, which are controlled before machining. After the forging, the pre-machining of the base or lid is done. After pre-machining, the base or lid is tested via ultrasonic testing. If the test does not show any relevant defects, the base or lid is machined to its final measures and shape.

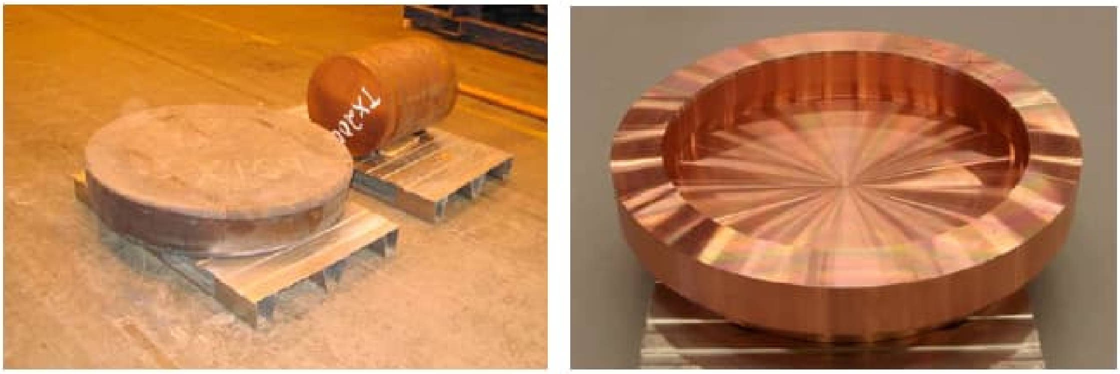


Figure 2-11: The left picture shows a copper ingot and a forged lid. The right picture shows a pre-machined lid. (SKB, 2010)

Welding of base to copper tube

For copper tubes that do not have an integrated base manufactured by pierce and draw method, welding of the base is necessary. In the KBS-3 concept, it is planned to use the same friction stir welding method as for the canister closure. There is no difference in the welding process between base and lid. The bases are manufactured as described in the previous section.

For friction stir welding, a rotating tool is used. The shoulder of the tool is made of a tungsten alloy called Densimet, and the probe of the tool is made out of a nickel based super alloy called Nimonic 105. The tool is changed after each weld made in order to prevent damaging of the tool and to ensure the repeatability of qualified welding. The welding is done in an argon atmosphere to prevent oxidation of the joint surfaces. The welding tool is shown in Figure 2–12.

Figure 2-12: Tool for friction stir welding (SKB, 2010)

During welding, the rotating tool is forced down into the weld metal. The tool is designed to heat up the metal by means of friction, through the shape of the tool and the rotation to force the plasticised metal to turn around and to create a weld. The shoulder of the tool also supports the heating process with additional friction and prevents the plasticised material to be forced out of the weld zone.

A welding cycle can be divided into several sequences, which can be seen in Figure 2-13. First, a hole is drilled 75 mm above the weld line, into which the rotating tool is then forced so that the copper is heated up. When the temperature of the tool has reached a specific level, the welding speed is accelerated to a constant value. After the acceleration sequence has been completed and the temperature of the tool has reached the required equilibrium temperature and has become stable, the tool is moved down to the joint line. Here, joint line welding is carried out. After a complete rotation, the tool is moved up 75 mm, where the welding cycle is completed, and the unavoidable exit hole is formed when the tool is extracted from the canister. Both the acceleration sequence and the exit hole are then machined away when the base is given its final dimensions.

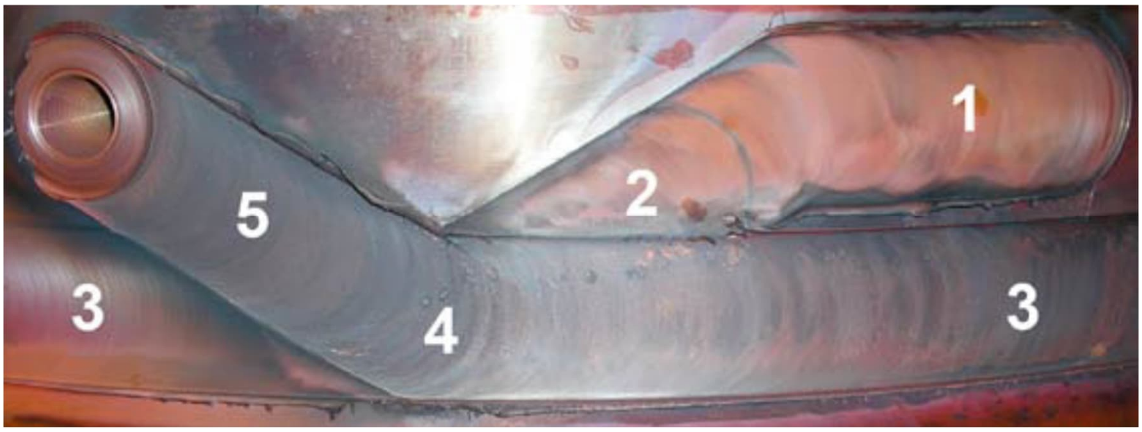


Figure 2-13: Sequences in the welding cycle: 1) acceleration sequence, 2) downward sequence, 3) joint line welding, 4) overlap sequence and 5) parking sequence (SKB, 2010)

2.3 Manufacturing of the DBD-v1 canister

Figure 2-14 shows a graphical illustration of all the working steps between canister production and disposal of the DBD-v1 canister.

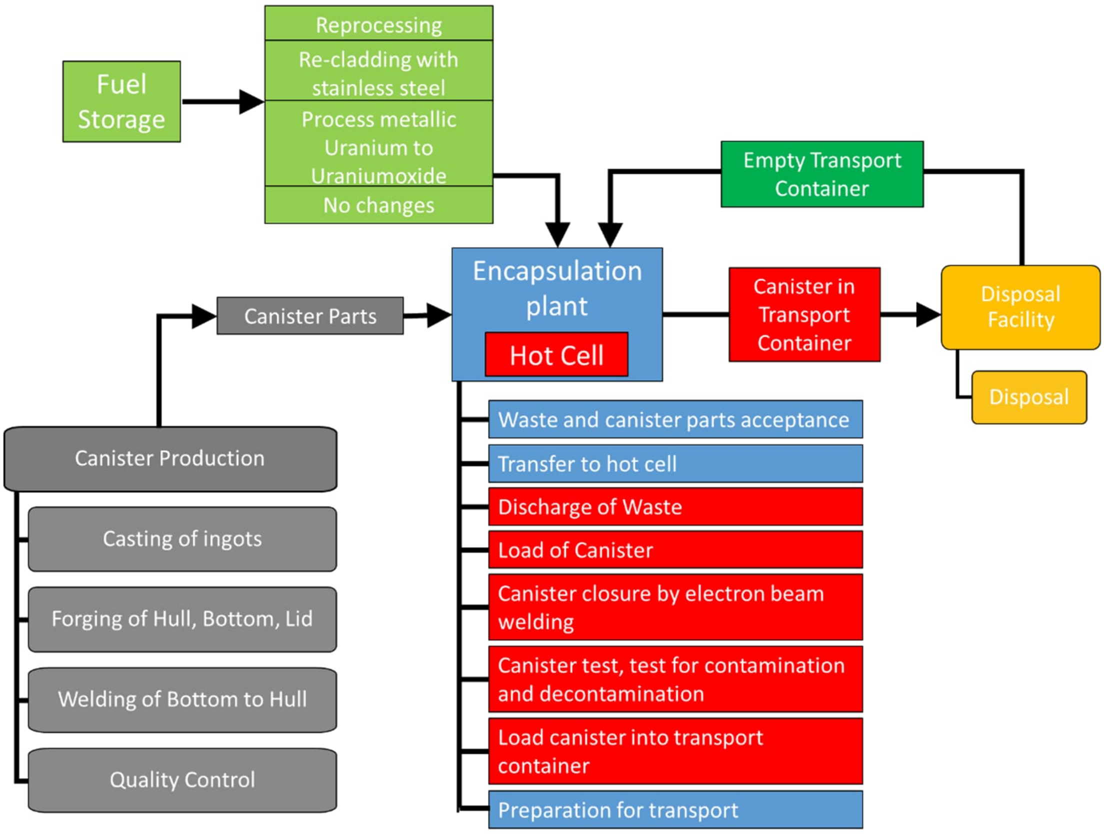


Figure 2-14: Graphical illustration of the working steps between canister production and disposal (Wunderlich et al. 2021).

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 tube, lid and bottom and mechanical processing

In the next step, the canister tube, 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 tube

In this step, the canister bottom is welded by either electron beam or other welding techniques, such as metal inert gas welding to the tube. After the welding, the weld should be machined and treated. Additionally, non-destructive testing is necessary to test the canister tube 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 fuel handling cell of the encapsulation plant.

Alternatively to welding the canister bottom to the tube in the canister production facility, this step can also be performed in the fuel handling cell using the available electron beam welding equipment.

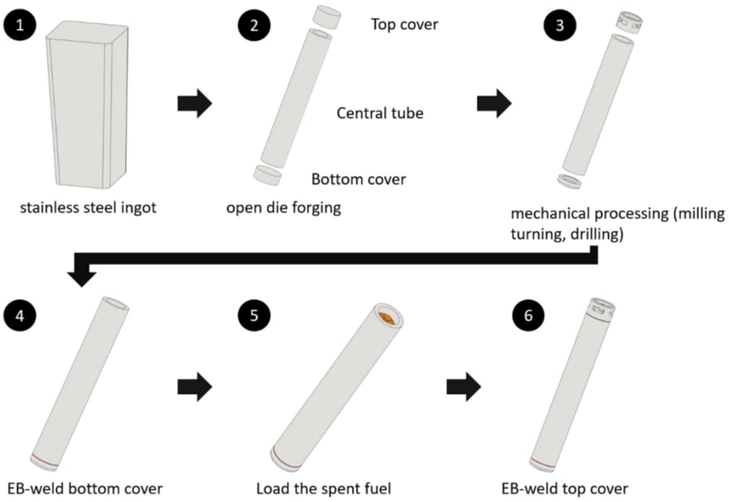


Figure 2-15: Illustration of the main steps during canister production and encapsulation (Wunderlich et al. 2021)

2.4 Analysis of the manufacturing processes

There are some main differences between the KBS-3 canister and the DBD-v1 canister, which lead to the main differences in canister manufacturing. The KBS-3 canister has an insert made of cast iron and the outer shell made of copper. It also has a larger diameter and length than the DBD-v1 canister. The DBD-v1 canister is made of stainless steel. Since the outside tube is load bearing itself, it does not need an insert. With the DBD-v1 canister, no production steps connected to the insert of the KBS-3 concept are needed. Only an insert for fuel rods is necessary for the DBD-v1 canister, but this will be a welded tube like the canister itself and not a cast structure.

Table 2-1: Overview of manufacturing of KBS-3 and DBD-v1 canister.

Canister component	KBS-3 canister	DBD-v1 canister
Insert	Insert made of cast iron with a welded tube cassette	No insert, fuel rods in an overpack or CSD-V bottles
Manufacture of wrought material	Copper ingots are casted for tube and lids	Stainless steel ingots are casted for tube and lids
Outer tube	Reference method by SKB is extrusion, which Posiva has studied as one option of manufacturing	The outer stainless steel tube is made by open die forging
Lid and bottom	Lid and bottom are forged	Lid and bottom are forged
Machining	Components are machined to final dimensions and surface roughness	Components are machined to final dimensions and surface roughness. Components are treated with a cold working method like shot peening to increase the resistance against pitting.
Welding	Bottom is welded to the tube using friction stir welding by use of customized welding equipment, tubes made with pierce and draw method have an integrated bottom	Bottom is welded to the tube using electron beam welding by use of customized welding equipment
Quality control	Components are controlled by non-destructive methods, such as ultrasonic, eddy current and visual	Components are controlled by non-destructive methods, such as ultrasonic

The manufacturing process of the canister tubes is comparable by both canister types. Both the copper tube (KBS-3) and the stainless steel tube (DBD-v1) can be produced by extrusion, pierce and draw method or forging. Currently the reference method for the DBD-v1 canister is open die forging. Prototype canister tubes for KBS-3 canisters have already been successfully produced on behalf of SKB and Posiva. The DBD-v1 canister is smaller but made of higher strength material, and thus it is expected that the process forces are somewhat comparable. Therefore, it can be stated that the DBD-v1 canister will be fabricable with equipment and machines comparable to the manufacturing of the KBS-3 canister tubes.

In the DBD-v1 canister and the KBS-3 canister, different methods for welding the base to the canister are used. In the KBS-3 canister concept, friction stir welding for the base is used. The DBD-v1 canister concept uses electron beam welding because friction stir welding is harder to control for austenitic stainless steel. Due to the higher hardness of steel to copper and the higher temperatures needed for welding, the possibility of tool damage increases when using friction stir welding for the tube of the DBD-v1 canister. Therefore, it was proposed to use electron beam welding for the DBD-v1 canister. In general, both welding methods seem comparable. The use of the welding techniques described above for both canister types will require specialised welding equipment. SKB uses a customized machine for friction stir welding. Also in the DBD-v1 concept some customization will be necessary because of the size and the weight of the canister. Additionally, the machine should be radiation hardened because usually electron beam welding equipment is designed to withstand x-ray but not neutron radiation, and damages to the equipment can occur. The electron beam welding will require a vacuum chamber at least around the welded surfaces while friction stir welding can be done in normal atmosphere.

All in all, there is not much difference between the manufacturing of the KBS-3 canister and the DBD-v1 canister that would give one concept an advantage over the other and, therefore, lead to a decision for that concept. On the other hand, the KBS-3 canister requires more NDT (non-destructive testing) inspection than the DBD-v1 one, because of the dual structure and double lids.

The difference between the canister concepts lies in the level of technical maturity of the manufacturing processes. The KBS-3 concept relies on a basic concept that was introduced in 1983 and has been developed since then. Several improvements to the canister concept have been done over the years. For the KBS-3 canister, Posiva and SKB have tested manufacture programmes. In all, more than 50 different inserts (47 BWR, 8 PWR and 3 VVER-type) have been produced until 2012. Results of the test production of five BWR and three PWR inserts are described in SKB (2010). All of the inserts met the specified requirements for material composition, material properties, geometry and dimensions. Also, safety relevant defects in the casting either did not occur or could be successfully detected with the used non-destructive testing methods. Problems met previously with bending of the steel tube cassette could be successfully prevented by filling the steel tubes with compacted sand before casting. Numerous copper tubes have been produced by SKB and Posiva. Regarding Posiva, 57 copper tubes have been produced. SKB states that 40 large copper ingots have been casted and 27 tubes have been produced by extrusion. SKB describes the results of eight tubes produced between 2005 and 2008. Overall, those tubes met the specified requirements for material properties, dimensions and geometry. Some problems occurred with the straightness of the tubes but could be solved by using guide tubes during extrusion. Safety relevant defects did not either occur or could be detected successfully by using the non-destructive testing methods. For both the insert and the copper tube, SKB and Posiva have continued the research on manufacturing and to qualify more suppliers for canister components but no published reports on the results are available.

For the friction stir welding of copper bottoms to the tubes, a customized welding equipment was designed and used in weld tests. In SKB (2010), a series of 20 tests under realistic production conditions is described. The results of the weld tests show that the friction stir welding process is robust and process properties are reliable. The test welds met the requirements for material properties and required weld thickness. The size of occurring defects in the weld could be further reduced by optimization of the weld tool. Safety relevant defects can also be found successfully with the used non-destructive testing methods.

All in all, it can be said that SKB, Posiva and their suppliers have extensive knowledge in manufacturing of the KBS-3 canisters. Therefore, it seems possible that the KBS-3 system can be implemented in Norway’s disposal programme without the need of substantial research and development. However, detailed adjustments to the canister will be necessary to fit it to Norway’s waste inventory. For NND, it is advised to closely follow Posiva and SKB on their way in implementing the KBS-3 in the future and their experiences during this process.

For the newly developed DBD-v1 canister, the level of technical maturity is not comparable to the KBS-3 concept. The DBD-v1 canister is the first design iteration for a deep borehole disposal canister for Norway. Nonetheless, the planned manufacturing methods for DBD-v1 are industry standards. Forging components equivalent to canister dimensions out of stainless steel is a widely used manufacturing technique in a lot of industries. Electron-beam welding is also an established and robust manufacturing process. Some customizations to the available equipment on the market will be necessary but no major changes to the welding technique will be required.

All in all, there are no indications that conflict with the manufacturability of the DBD-v1 canister. The used manufacturing techniques are established, and no new manufacturing techniques need to be introduced for manufacturing of the canister. For the DBD-v1 canister to reach the same level of maturity as the KBS-3 canister, it will first be necessary to develop the general concept and assess the performance of the post-closure safety of the DBD concept. After that, it will be necessary to manufacture some prototype canisters and check whether they meet the specified requirements.

3 ENCAPSULATION OF SPENT NUCLEAR FUEL

3.1 Introduction

The generic encapsulation processes for the KBS-3 and DBD-v1 canisters are described in this chapter. Previous studies suggest that both canister designs are suitable for Norwegian fuel types and for vitrified waste if the spent fuel was to be reprocessed (Juutilainen et al. 2020, Loukusa & Nordman 2020, Wunderlich et al. 2021).

Since most of the spent fuel inventory consists of metallic uranium in aluminium cladding, it is expected that this fuel type would be re-contained (e.g. in stainless steel casing) to meet the requirements of durability and airtightness with respect to the fuel handling in the encapsulation plant. It should also be noted that some of the current inventory consists of single rods which should be assembled into packages of several rods to enable fuel transfer operations in the fuel handling cell within reasonable time. Failed or damaged fuel should also be placed in intact overpacks before entering the encapsulation process.

The described processes are based on an assumption that the canisters are NDT inspected and the KBS-3 canister is preassembled (cast iron insert is placed inside the copper shell) before its reception at the encapsulation plant. It is also expected that the bottom cover of the canisters has been welded to the central tube during the manufacturing process of the canister unless the canister is manufactured by pierce and draw method where the bottom cover is integrated in the copper tube.

It must be emphasized that the following encapsulation process descriptions are simplified and do not involve, for example, detailed descriptions of lifting operations of the spent fuel transport cask and canister in the reception hall. The detailedness of the descriptions is determined by the essential steps and systems that are necessary for the encapsulation of spent nuclear fuel to meet the long-term safety requirements of the disposal canister.

3.2 Encapsulation of the KBS-3 canister

3.2.1 Introduction

Encapsulation of spent nuclear fuel in a KBS-3 type canister has been studied by SKB from the early 1980s. Soon after the introduction of the KBS-3 canister in 1983, the concept was also adopted in Finland by TVO and thereafter by Posiva Oy. Currently, Posiva is constructing an encapsulation plant at Olkiluoto, and different systems used in encapsulation (e.g. friction stir welding, fuel handling cell, NDT inspection) are being manufactured and partly in the phase of Factory Acceptance Testing (FAT).

The following encapsulation process description applying to the KBS-3 canister is based on the current plans in Finland. Streamlining of the process considering the spent fuel in Norway is discussed in Chapter 5.

The phases of the encapsulation process planned for the Olkiluoto plant, which will be located above the spent nuclear fuel repository, are presented in Figure 3-1.

Figure 3-1: Cross section of Finnish encapsulation plant. 1. Transport cask reception hall, 2. Fuel handling cell, 3. Canister transfer corridor, 4. Welding chamber, 5. Machining and NDT inspection station, 6. Canister hoist station, 7. Canister lift. (Kukkola 2012).

In the following sections, processes of the encapsulation are described in flow charts where the main processes are identified by different abbreviations:

- TC=Transport Cask
- CA=KBS-3 Canister
- HC=fuel Handling Cell
- DBD=DBD canister

3.2.2 Process of the transport cask

Spent fuel is transported from the interim storage to the reception hall of the encapsulation plant. In the reception hall, a bridge crane lifts the transport cask down to the transfer trolley (Figure 3-3), which is positioned in the transfer corridor beneath the reception hall (TC-1).

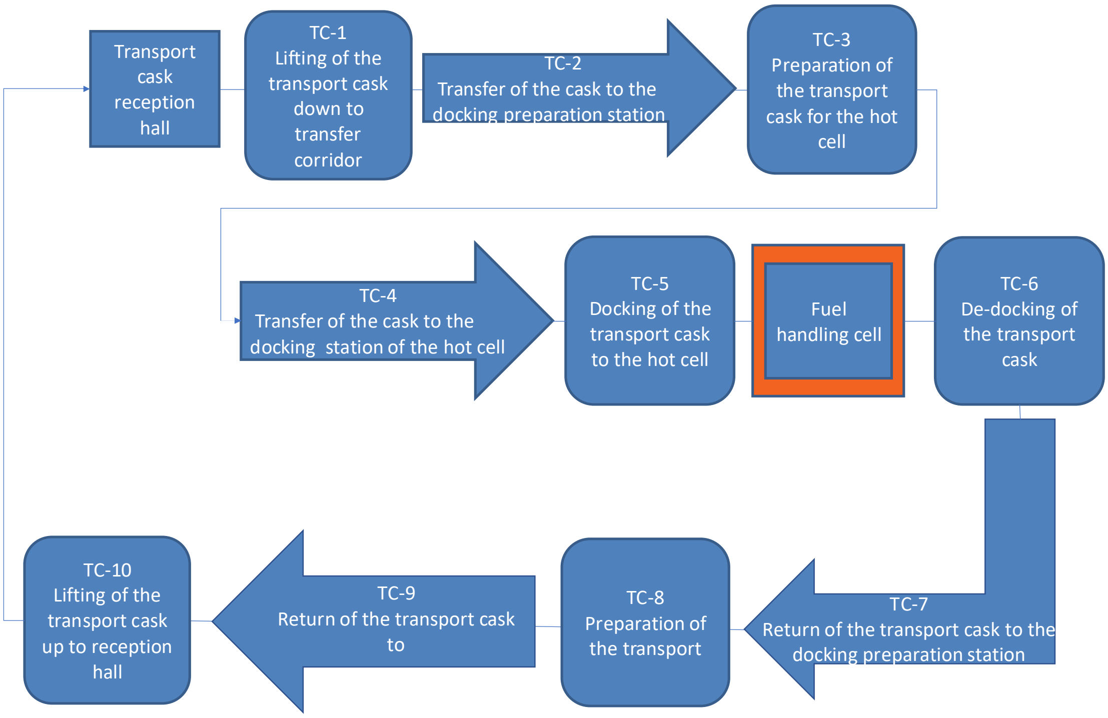


Figure 3-2: Process of the transport cask

The transfer trolley is remotely operated and is transferred to the docking preparation station (TC-2), where the pressure of the cask is equalized, a gas sample from the interior of the cask is taken (with vitrified waste not needed), a lifting crown is attached to the lid of the cask, and the screws of the lid are loosened (TC-3). The transport cask is transferred to the docking station of the fuel handling cell (fuel handling cell) (TC-4).

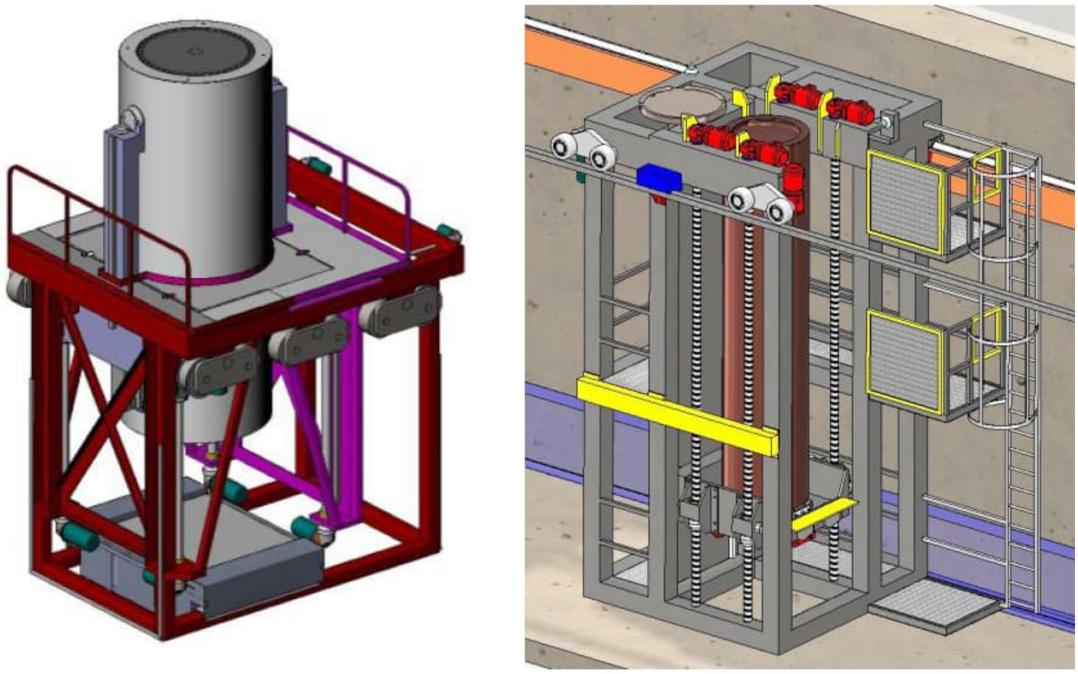


Figure 3-3: Transport cask transfer trolley (left) and canister transfer trolley (right) (Kukkola 2012, Suikki 2011)

The lifting table of the transfer trolley lifts the transport cask up into the opening of the fuel handling cell. The transport cask is locked in the opening, the radiation cover of the opening is moved aside, and the lid of the transport cask is lifted up and lowered in the storage position. A protective cone is installed in the docking opening to protect the transport cask from mechanical damage and from contamination by water splashes or stray particles (crud) during unloading of fuel assemblies (TC-5). The transport cask is ready for fuel removal.

After the fuel removal, the transport cask will be disengaged from the docking station (TC-6), transferred to the docking preparation station for contamination check (TC-7 – TC-8) and then below the hatch of the reception hall and lifted to the reception hall for return (TC-9 –TC-10).

3.2.3 Process of the canister before fuel transfer

Pre-assembled canister with a copper shell and cast iron insert is lifted from the storage position in the canister component storage down to the canister transfer trolley (Figure 3-3) in the canister transfer corridor. The copper lid is lifted separately down to the lid lifter device of the transfer trolley (CA-1).

The transfer trolley with the canister is transferred below the opening of the welding station (CA-2).

The lid lifter device of the transfer trolley lifts the copper lid up to welding chamber. The lifting gripper of the welding station catches the copper lid from the lid lifter of the transfer trolley into the welding chamber (CA-3).

The canister transfer trolley is moved below the docking station of the fuel handling cell (CA-4).

The lifting table of the transfer trolley lifts the canister into the opening of the fuel handling cell, the sealing rings of the docking station are pressurized and tested. The canister is ready for the operations of the fuel handling cell (CA-5).

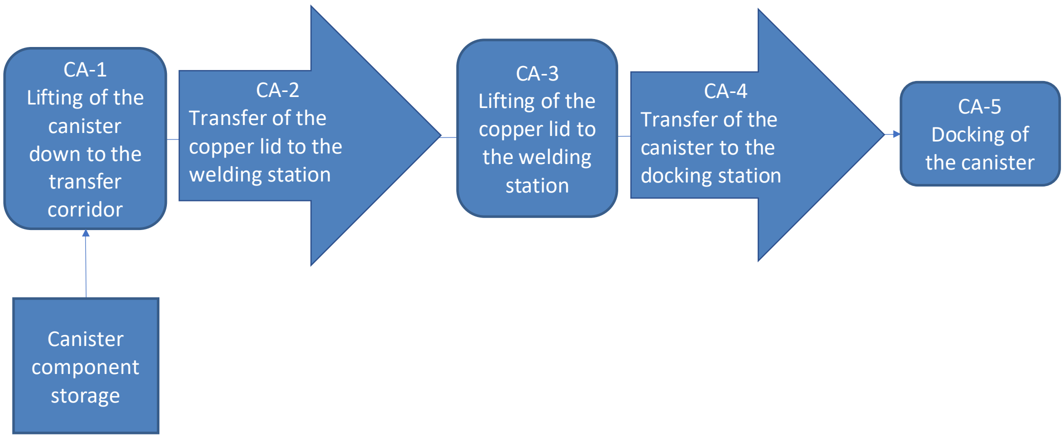


Figure 3-4: Process of the canister before fuel transfer.

3.2.4 Process of the fuel handling cell

In the fuel handling cell, the spent fuel bundles are transferred by means of a bridge type handling machine which moves along the rails inside the handling cell (Figure 3-5). The operations are semi-automatically steered from the control room adjacent to the handling cell. The semi-automatic control implies that the device can perform certain move combinations independently, but for any operations requiring more precise control, the operator must control the device or, at a minimum, accept the following sequence of operation.

Before the transfer of the spent fuel bundles from the transport cask, the cover hatch of the canister docking station is opened (HC-1, see also figure 3-7). The gas exchange cap is lowered on the canister top, and the screwdriver inside the cap opens the lid which is attached to the magnetic gripper and lifted up. The gas exchange cap moves aside (HC-2). Protective cone is lowered on the top of the canister to protect the sealing faces of the canister from contamination (HC-3). The lid of the drying station is opened, and the fuel handling machine lifts spent fuel bundles one by one from the transport cask into the drying station (HC-4). Dry spent fuel bundles can be transferred directly into the canister (HC-6). Once the spent fuel bundles have been dried (HC-5), one sample is taken to the gamma measurement station to confirm the source term of the fuel (HC-5B). The measurement is registered by the IAEA. Once all the fuel bundles that can be fitted in one canister have been transferred (HC-6), the lid of the drying station is closed, the protective cone of the transport cask is moved aside, and the protective cover on the opening of the transport cask docking station is closed.

Figure 3-5: Fuel handling cell: 1. Fuel handling machine, 2. Transport cask docking station, 3. Drying stations, 4. Measuring stations, 5. Canister docking station (Suikki 2012)

Before the canister will be closed, all fuel bundles are identified and verified by the regulator and the IAEA (HC-7). The protective cone is lifted up (HC-8), the gas exchange cap is lowered on the canister top, the inner lid is loosely fastened and the atmosphere inside the canister is changed to argon and the lid is tightly fastened (HC-9). The contamination of the canister top is checked, and if needed, the canister top is cleaned (HC-10). The covering hatch of the docking station is closed (HC-11).

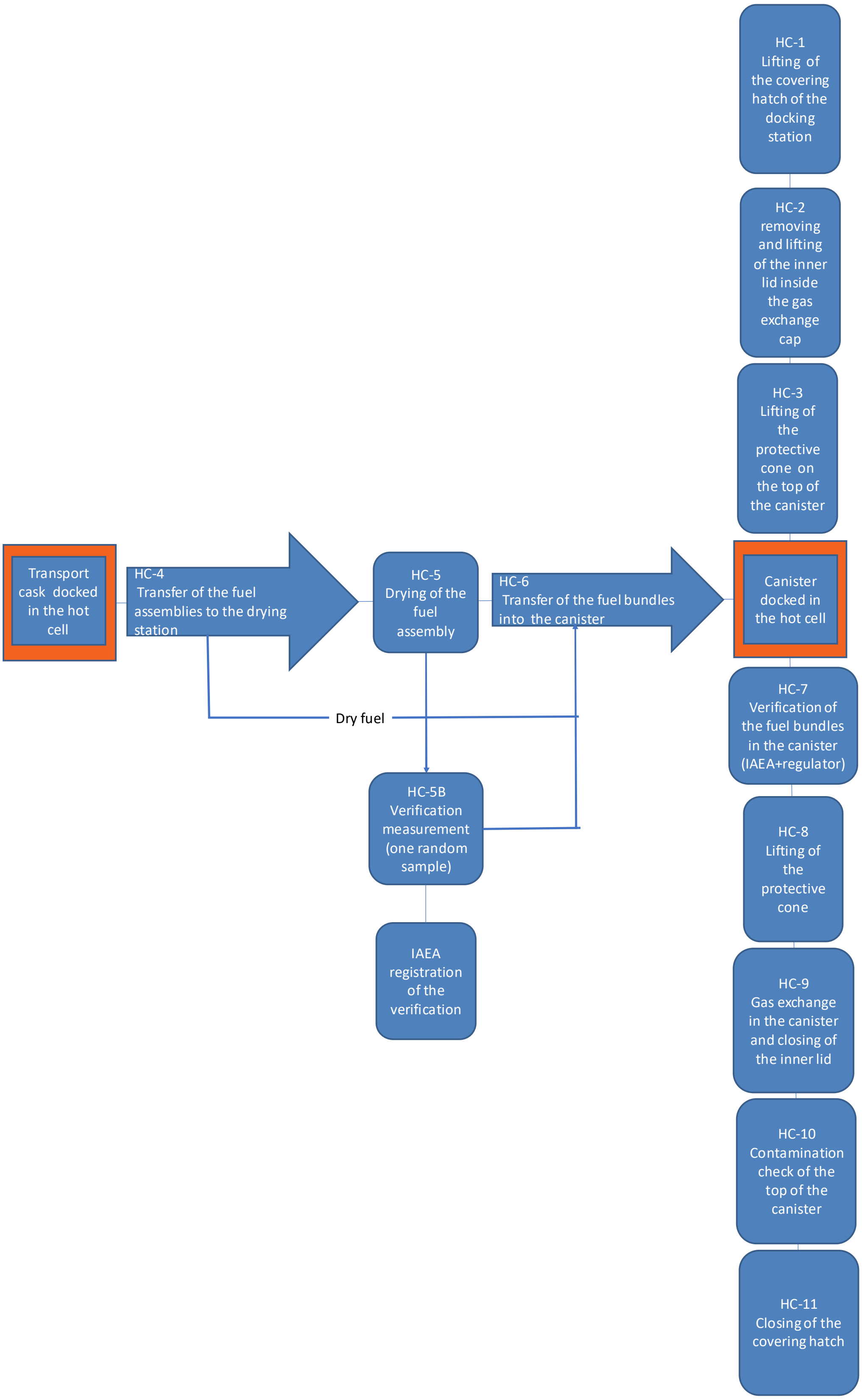


Figure 3-6: Process of the fuel handling cell.

Figure 3-7: Equipment at the canister docking station: gas exchange cap on the left, covering hatch in the middle and protective cone on the right (Suikki 2006)

3.2.5 Process of the canister after the fuel transfer

After the encapsulation in the fuel handling cell, the contamination of the upper part of the canister will be checked, the lid of the canister will be welded, machined and NDT inspected before the canister is ready for transport (Figure 3-8). For the welding method, Posiva has chosen friction stir welding (FSW) in 2014, which has proven to have better properties compared to electron beam welding (EBW) (Posiva Oy, 2014).

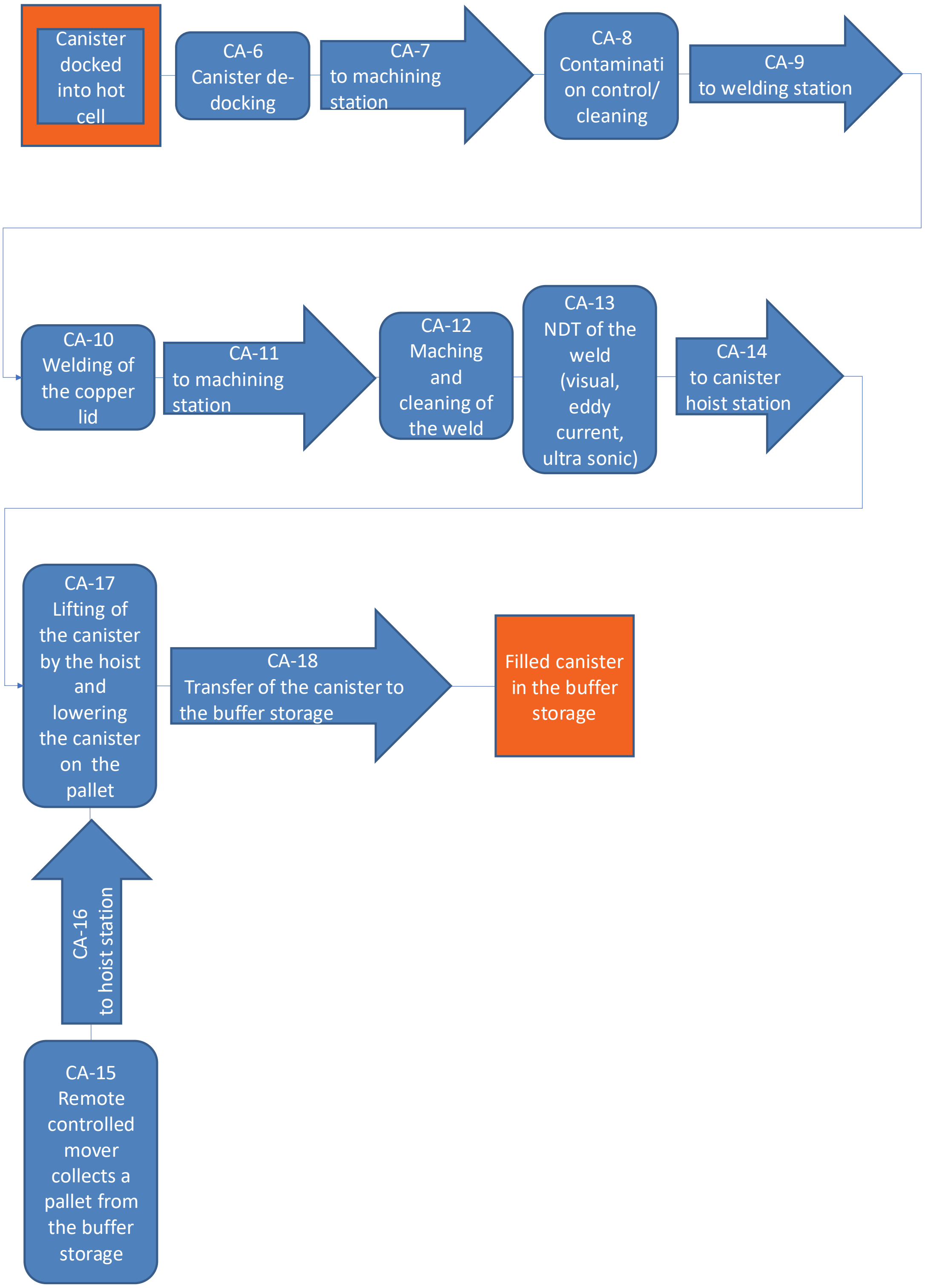


Figure 3-8: Canister process after the fuel transfer.

The sealing rings of the canister docking station are de-pressurized and the lifting table of the transfer trolley lowers the canister down from the opening of the fuel handling cell (CA-6).

The canister is transferred below the opening of the machining station (CA-7).

The lifting table of the transfer trolley lifts the canister into the opening of the machining station. A sample is taken from the upper part of the canister for contamination check. If contamination is found, the upper part of the canister is cleaned. The lifting table of the canister transfer trolley lowers the canister down (CA-8).

The canister is transferred below the opening of the welding station (CA-9).

The lifting table of the transfer trolley lifts the upper part of the canister into the welding chamber. The centricity and elevation of the canister are verified by the laser scanner, main canister clamp is actuated, shield chamber closes, and argon purge starts. Lid is lowered onto the canister, and the lid gripper mechanism is released. Full clamping pressure is applied to the lid. Weld seam argon purge starts following the welding of the lid. After welding, the gas shield chamber opens, the lid and canister clamps are retracted and the transfer trolley lifting table lowers, removing the canister from the weld chamber (CA-10).

The transfer trolley moves the canister below the opening of the machining station (CA-11).

The lifting table of the transfer trolley lifts the upper part of the canister into the machining station. The rotating unit of the machining station is locked, while the rotation of the lifting table of the transfer trolley is unlocked enabling the rotation of the canister. The weld is machined to meet the requirements of the NDT inspection. After machining, the upper part of the canister is cleaned, and the quality of the machining is checked (CA-12).

NDT inspection of the weld takes place in the machining station, which is equipped with ultrasonic and eddy-current testing devices. Visual inspection of the weld can be done with cameras assembled in the station. After NDT inspection, the lifting table of the transfer trolley is locked, and the rotating unit of the machining station is unlocked. The lifting table lowers the canister down in the transfer trolley (CA-13).

The canister transfer trolley moves the canister below the hoist station (CA-14).

A remote-controlled mover collects a pallet from the canister buffer storage and brings it to the canister hoist station (CA-15–16).

The lifting table of the canister transfer trolley lifts the canister, the gripper of the hoist lowers on the lid of the canister and the horizontally moving jaw of the gripper penetrates under the lifting cover of the copper lid. The hoist lifts the canister up, the lifting table is lowered, and the transfer trolley moves aside. The hoist lowers the canister on the pallet that is resting on remote controlled mover (CA-17). The remote-controlled mover transfers the canister to the buffer storage before transfer down to the repository (CA-18).

3.3 Encapsulation of the DBD-v1 canister

The generic encapsulation process for the DBD-v1 canister is described by Wunderlich et al. (2021). The encapsulation process of the DBD-v1 canister is planned with the following steps.

3.3.1 Acceptance of spent nuclear fuel and canister components

Spent nuclear fuel 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 fuel handling 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 canister parts fulfil the quality requirements, they are accepted and stored or can be alternatively transferred to the fuel handling cell.

3.3.2 Transfer to the fuel handling cell

Because of the radiation, the canister loading can only take place inside a fuel handling cell, which is adequately shielded. If the welding of the bottom to the tube will also be done in the fuel handling cell, the welding (and the related test) is done first without any radioactive material inside the fuel handling cell to simplify the processes. After the welding, the weld between the tube and bottom should be inspected with non-destructive techniques, such as ultrasonic testing or X-ray. Machining of 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 fuel handling cell.

After the canister has been prepared, the spent fuel transport cask can be docked to the fuel handling cell for the fuel transfer.

3.3.3 Unloading of the spent fuel transport cask

When the transport cask is docked to the fuel handling cell, the cask can be opened for the transfer of spent fuel bundles. The docking station of the transport cask is close to canister loading to keep the transfer distance of unshielded spent fuel bundles as short as possible to minimise radiation.

3.3.4 Loading of canister

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

3.3.5 Canister closure by electron beam welding

The canister closure 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.

3.3.6 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 testing of the weld is usually carried out with non-destructive testing methods such as ultrasonic testing or X-ray.

Due to the low number of weld seams, including another quality assurance method seems 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 will be determined. When using these process parameters in the welding process, it seems statistically possible that, with the small number of welds, all welds should be leak tight and meet the quality requirements.

In addition to the test of the welds, a test for contamination on the canister surface is necessary. If needed, decontamination of the canister must be possible in the encapsulation plant.

3.3.7 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.

3.3.8 Preparation for transport

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

4 ADAPTATION OF ENCAPSULATION FOR NORWAY

4.1 Comparison

The encapsulation process for the KBS-3 canister is more demanding than for the DBD-v1 canister, which is smaller in size and structurally simpler. In addition, requirements for the long-term durability of DBD-v1 canister are not as strict as for the KBS-3 canister, because in the deep borehole concept much more emphasis is put on the natural barrier (bedrock) to keep radionuclides out of biosphere. The greater depth of disposal suggests that the purpose of the canister is to serve as a container that enables the transport of spent nuclear fuel into the disposal depth rather than being an engineered barrier for the spent fuel.

The main differences of the processes are related to the canister itself. The KBS-3 canister has a dual structure with a cast iron insert and copper shell. In addition, the KBS-3 canister has two lids, the inner steel lid and the outer copper lid. The differences in the canister designs determine the process and systems that are needed in different phases of the process. The main differences are related to the processes in the fuel handling cell, welding station and machining station.

Followed from the different canister design the following process steps are not needed in the encapsulation of the DBD canister:

- gas exchange of the canister is not needed, because the DBD canister does not have to be resistant for internal corrosion initiated by the residual oxygen and nitrogen in the canister,
- process and systems for the removal and attachment of the inner lid are not needed,
- the steel lid of the DBD canister does not require friction stir welding
- the weld of the DBD canister lid does not require machining, because electron beam welding is applied.

4.2 Assumptions in the encapsulation processes

Before encapsulation, some of the Norwegian spent nuclear fuel needs pre-treatment before being 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 transferring operations in the fuel handling cell are possible.

Unlike in the Finnish process, the drying of the wet fuel bundles is not considered necessary in Norway, where the amount 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.

Regarding the canisters, it is assumed that the canisters are NDT inspected, and the KBS-3 canister is preassembled (cast iron insert is placed inside the copper shell) before its reception at the encapsulation plant. It is also expected that the bottom cover of the canisters has been welded to the central tube as part of the manufacturing process of the canisters.

4.3 Key features of the processes

Stemming from the concept description for Norwegian National Disposal Facility (Ikonen et al. 2020), the following differences compared with the Finnish encapsulation process can be identified:

- After the encapsulation, the canister would be transported to the disposal facility either via an access tunnel down to the KBS-3 repository in a DGR or to the disposal rig in the case of DBD, suggesting that a canister lift is not needed.

- Considering the small number of canisters to be disposed of (about 30 canisters for the DGR and 90 canisters for DBD), no buffer storage nor related transfer operations and systems for packed canisters would be needed. A canister filled with spent fuel would be transported to the disposal facility directly and not stored in the encapsulation plant or elsewhere while waiting for disposal.

Regarding the operations of the spent fuel transport cask, no changes would be introduced to the process describing the KBS-3 encapsulation (see Section 3.2.2). The design of the transport cask for Norwegian spent fuel is not determined yet, but the systems and equipment of the encapsulation plant can be modified and adjusted to whatever the design of the transport cask will be. For instance, the encapsulation plant under construction in Olkiluoto (Finland) is planned for handling three different transport casks corresponding to the different spent fuel assemblies (OL1-2, OL3 and LO1-2). The design of the transport cask affects, i.e., to the following equipment and systems of the encapsulation plant:

- bridge crane that lifts the transport cask in the reception hall
- transport cask transfer trolley
- dimensions and systems of the fuel handling cell docking station
- operations of the transport cask lid before and after the fuel transfer

Most of the measures to downscale the encapsulation process are related to the operations of the canister in the encapsulation plant. The operations of the canister during encapsulation could be simplified if the canister transfer corridor were replaced by a drive-through hall where the canister is moved by a special vehicle. Given that the canister would be placed into the transport cask before encapsulation no extra shielding for radiation would be needed after the canister is packed with nuclear fuel. The docking of the canister in the fuel handling cell and other stations of the encapsulation plant requires vertical movement of the canister. This could be realised, for example, by a piston that pushes the canister upwards inside the transfer cask. The encapsulation process with the canister inside the transport cask would be suitable for the DBD canister, which is smaller and needs no rotation during encapsulation operations.

Canister lids (two lids in the KBS-3 canister and one lid in DBD) would be either separately brought to the welding station or lid(s) could be transferred with the canister.

In the proposed encapsulation process, the canister moves only forward and is docked on its way to the fuel handling cell, welding station and integrated machining and NDT inspection station. The contamination check of the canister after the insert of the spent fuel would take place in the fuel handling cell. The encapsulation solution for NND is a “car wash” concept.

5 ENCAPSULATION PLANT CONCEPT FOR NORWAY

5.1 Introduction

In the following, streamlined encapsulation processes for Norwegian spent nuclear fuel are described for the KBS-3 and DBD-v1 canisters. The assumptions were listed in Section 4.2.

5.2 Encapsulation process for the KBS-3 canister in Norway

In the following, the modified process of the encapsulation of the KBS-3 disposal canister is described. Since the process related to the transport cask of spent nuclear fuel corresponds to the one described previously in the Section 3.2.2, it will not be described here.

The NDT inspected canister arrives at the canister reception hall of the encapsulation plant (Figure 5-1). The canister is turned to a vertical position on a transport dolly and lifted into the transfer trolley (CA-1) positioned on the transfer corridor below the reception hall. The copper lid is lifted from the truck on the lid lifter of the transfer trolley (CA-2). The trolley transfers the canister under the fuel handling cell (CA-3). The lifting table of the transfer trolley lifts the canister up to be docked to the fuel handling cell (CA-4).

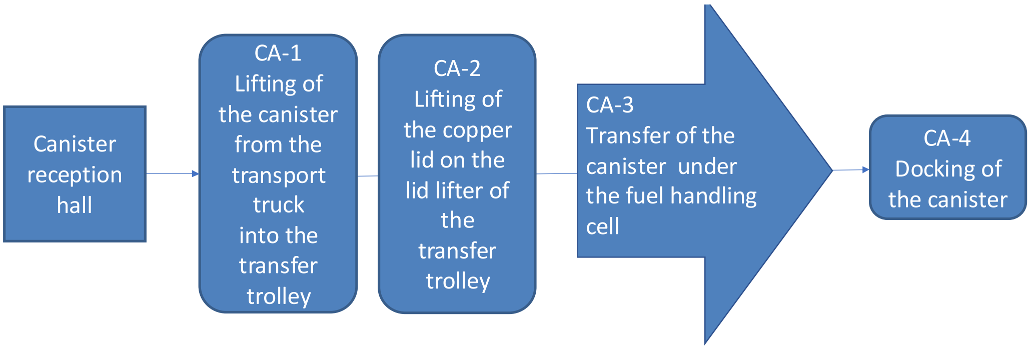


Figure 5-1: Process of the canister before fuel handling cell.

Once the canister is docked in the fuel handling cell, the covering hatch of the docking station will be opened (HC-1; see Figure 5-2). The gas exchange hood is lifted on the top of the canister, and the remotely operated screwdriver opens the central screw in the inner lid, after which the lid is fastened with a magnet to the gripper that lifts the lid. The hood moves aside with the lid in it (HC-2). The protective cone is lowered on the top of the canister (HC-3). The transfer of the fuel bundles from the transport cask into the canister starts (HC-4). One random sample of fuel bundles is taken to the gamma measurement station to verify the origin of the spent fuel. The measurement is registered by the IAEA (HC-4B). Once the fuel bundles have been placed in the canister, the IDs of the fuel bundles are registered and verified by the regulator and the IAEA (HC-5). The protected cone is lifted up from the canister top (HC-6). The gas exchange hood moves on the canister top, and the inner lid is loosely fastened. The canister is vacuumed and filled with argon gas; the lid is tightly fastened (HC-7). The contamination of the canister top is measured, and the canister will be decontaminated if needed (HC-8).

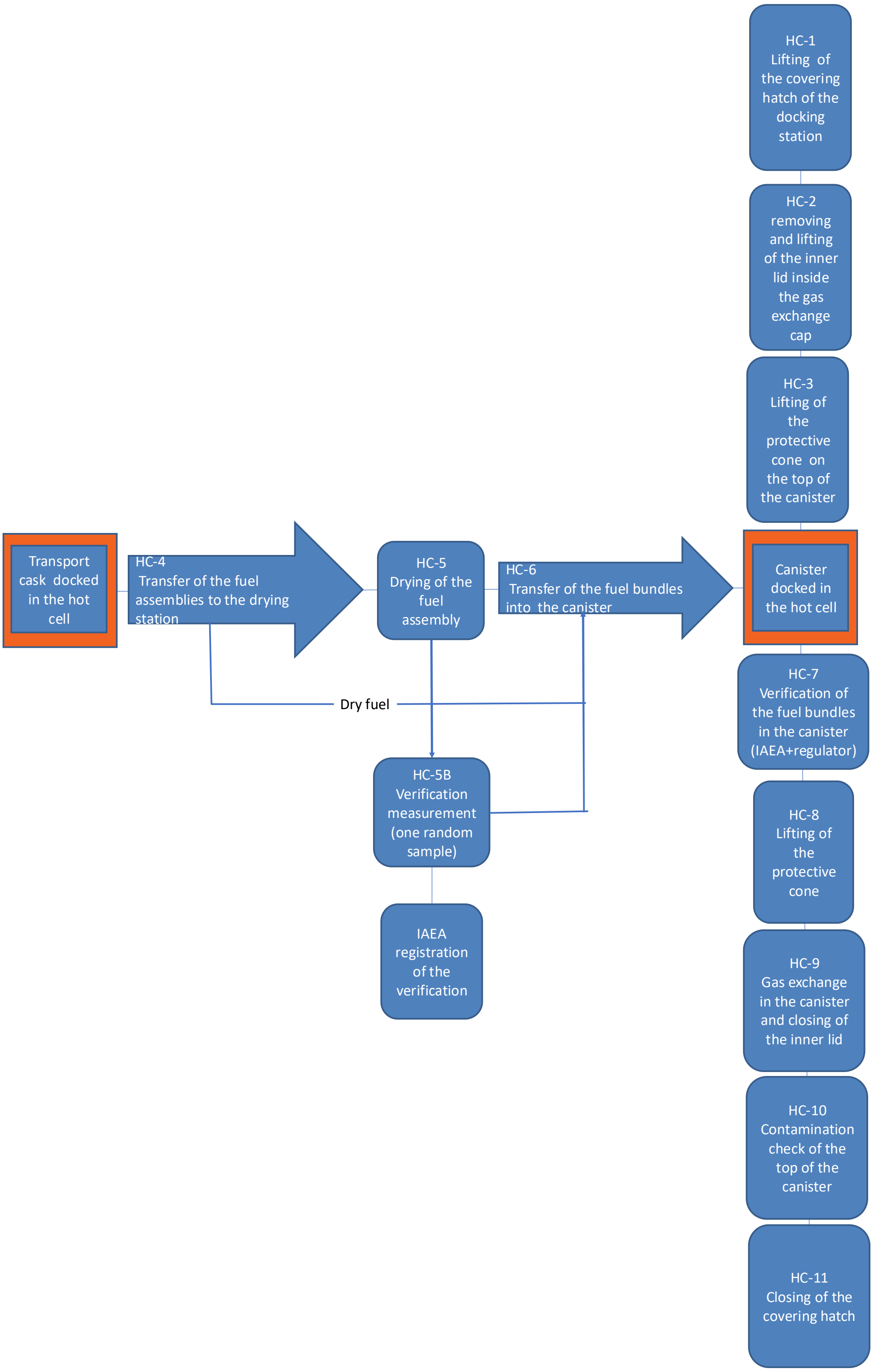


Figure 5-2: Process of the fuel handling cell.

After the canister top is found to be clean in the fuel handling cell, the canister is disengaged from the docking station and lowered down in the transfer trolley (CA-5; see Figure 5-3). The transfer trolley moves under the welding station (CA-6). The lid lifter of the transfer trolley lifts the copper lid up and the gripper in the welding chamber lowers and catches the lid that is lifted into the welding chamber (CA-7). The top of the canister is lifted up into the welding chamber (CA-8). Canister is positioned and clamped, the gas shielding is set, and argon purge starts (CA-9). The copper lid which is attached to the gripper is lowered on the canister top and clamped (CA-10). The lid is welded as the canister is rotated in the welding carousel (CA-11). After welding, the gas shielding is opened and the lid and canister clamp are retracted (CA-12). Canister is undocked and transferred to the machining station (CA-13–14). Canister is docked in the machining station (CA-15).

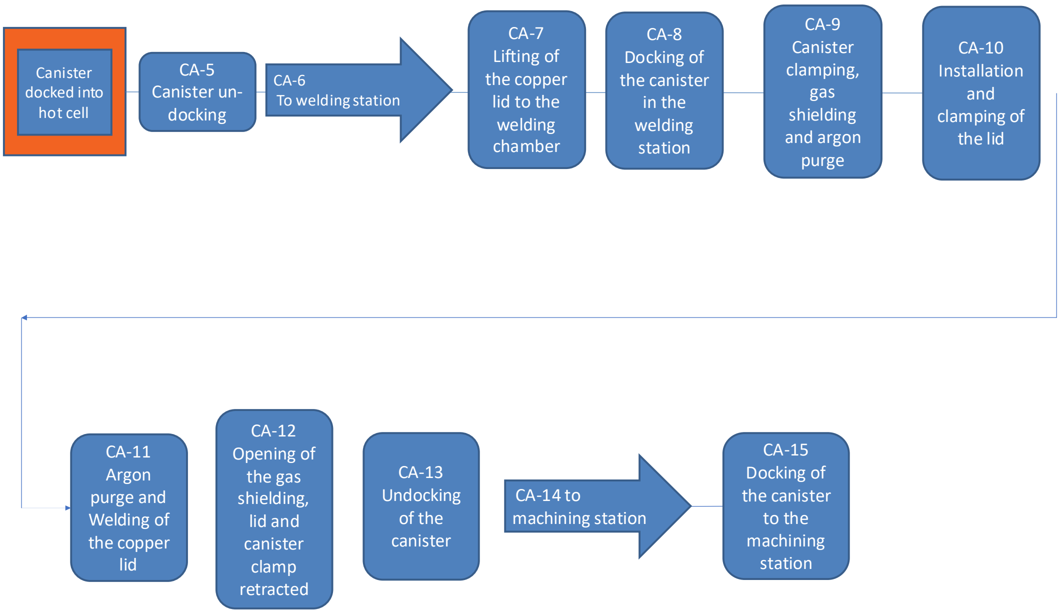


Figure 5-3: Welding process of the KBS-3 canister.

At the machining station, the rotating table of the transfer trolley is released (CA-16; see Figure 5-4), chip removal vacuum is started, and the weld is machined while the canister is rotating (CA-17). The weld is cleaned, and the quality of the machining is checked (CA-18). The weld is NDT inspected visually and by using ultrasonic and eddy current technique (CA-19). The rotation of the canister is locked, and the canister is undocked from the machining station (CA-20) and transferred to the hoist station (CA-21). At the hoist station the lifting table of the transfer trolley raises the canister, the gripper of the hoist lowers and fastens to the canister lid and raises the canister up, while the canister transfer trolley moves aside (CA-22). The hoist lowers the canister into the transport cask which is positioned in the lower level beneath the hoist station (CA-23). The bridge crane transfers the cover lid on the transport cask, the lid is fastened, and the cask is lowered horizontally. The canister is ready to be transported to the repository.

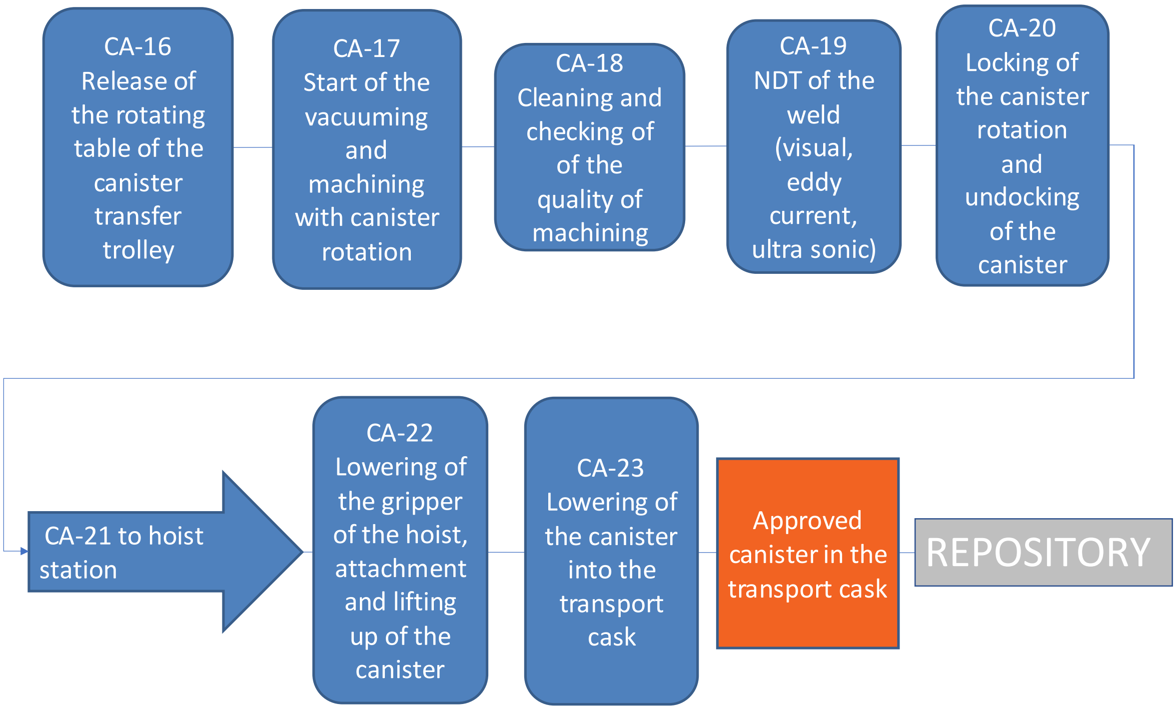


Figure 5-4: Machining and NDT inspection of the KBS-3 canister.

5.3 Encapsulation process for the DBD-v1 canister in Norway

For the description of the encapsulation plant for the DBD-v1 canister, it is expected that it is placed right next to the disposal borehole at National Facility site. In the first step of encapsulation, all necessary components are brought to the respective acceptance buildings at the National Facility. The spent fuel is brought in transport casks which can be docked to the fuel handling cell. The process related to the spent fuel transport cask is very similar to the corresponding process in the KBS-3 concept. Therefore, it is not further described here, and the description can be found in Section 3.2.2. For the drive-through encapsulation process, the encapsulation plant has two levels. The encapsulation process itself takes place on the first level where the fuel handling cell, welding chamber and the NDT chamber are located. The canister transfer takes place in a transfer corridor on a lower level. All the intersections between the transfer cask and the encapsulation plant take place from this transfer corridor and through the floors of the respective rooms.

In the first step, the canister parts are brought to the canister reception hall and there put into the shielded transfer cask trolley (DBD-1; see Figure 5-5). The transfer cask trolley is then used for the transfer to the fuel handling cell (DBD-2) and docked to the lock under the fuel handling cell (DBD-3).

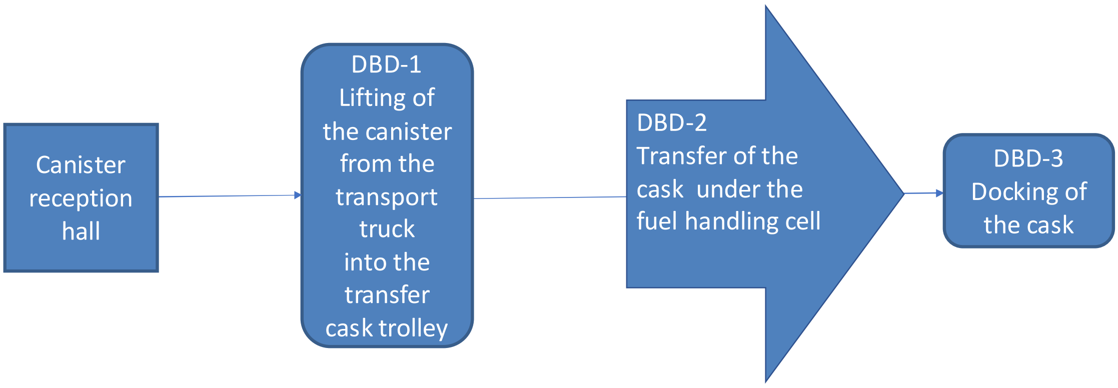


Figure 5-5: Process before the fuel handling cell for the DBD-v1 canister.

When the canister arrives below the fuel handling cell, the transfer cask is lifted up and docked with its upper lock to the lock of the fuel handling cell. Once the locks are connected, the corresponding sliders can be opened (HC-1; see Figure 5-6) and the transfer cask is connected with the fuel handling cell. The canister is then pushed into the fuel handling cell by a piston coming through the lower lock of the transfer cask (HC-2). The lid resting loose on the canister top is then lifted off and stored at its storage position (HC-3). Then a protective cone is placed on the canister so that contamination cannot fall into the transfer cask (HC-4).

When the spent fuel transport cask is also docked to the fuel handling cell, the transfer of fuel bundles starts. Before the transfer, a gas sample is taken from the transport cask to check for leaky fuel elements. A verification measurement for the source term of the spent fuel is also done with one randomly selected fuel bundle using gamma measurement (HC-5B). Results are also documented for IAEA verification. During the spent fuel transfer, the spent fuel IDs are documented for the verification by the IAEA and the regulator (HC-6). When the spent fuel transfer is finished, the protective cone is lifted away from the canister (HC-7). The canister top and surface are then checked for contamination, and if necessary, they are decontaminated (HC-8). After that, the canister lid is placed back on the canister (HC-9) and the canister is lowered down into the transfer cask trolley (HC-10) and docked off from the fuel handling cell (DBD-4; see Figure 5-7).

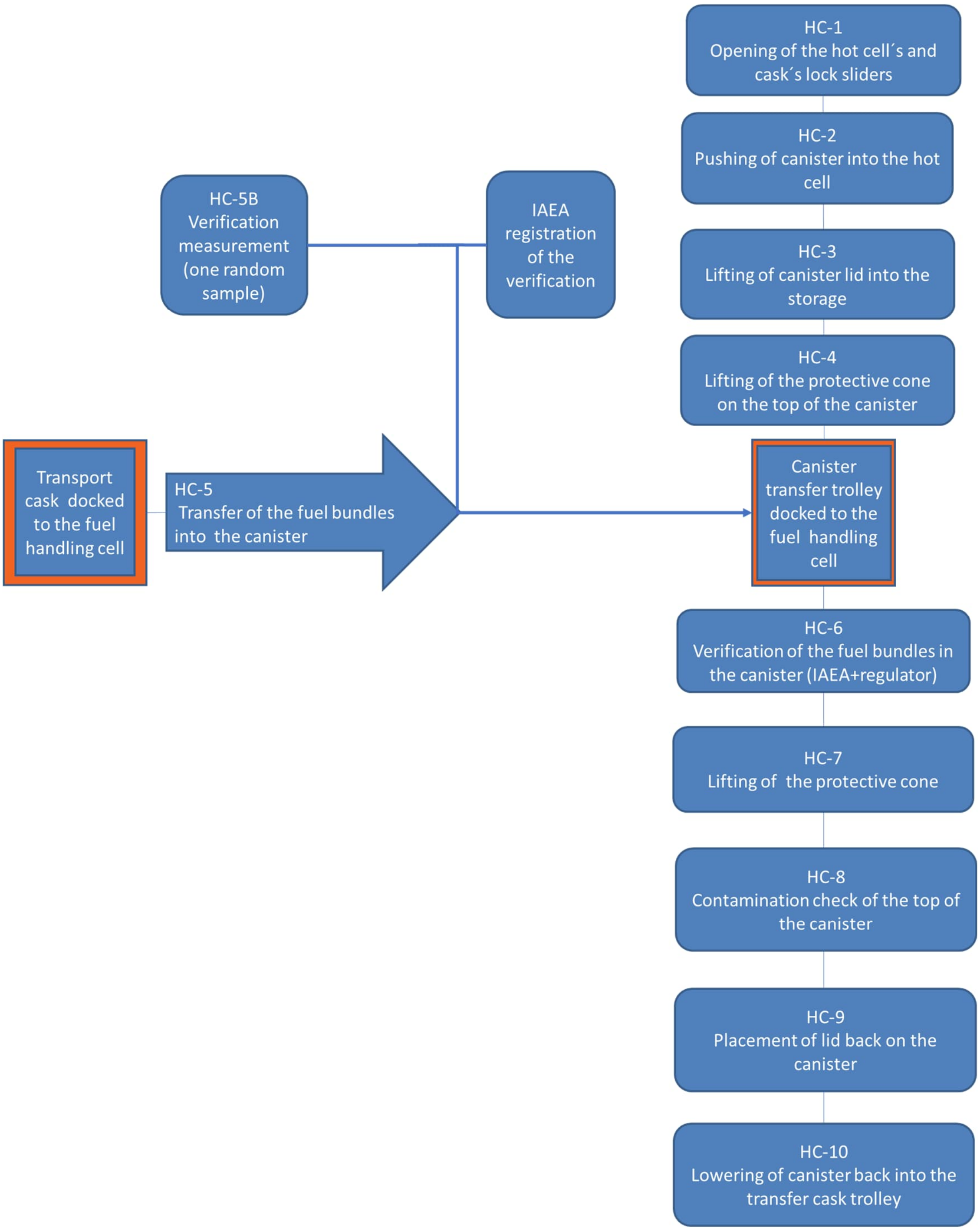


Figure 5-6: Processes inside the fuel handling cell for the DBD-v1 canister.

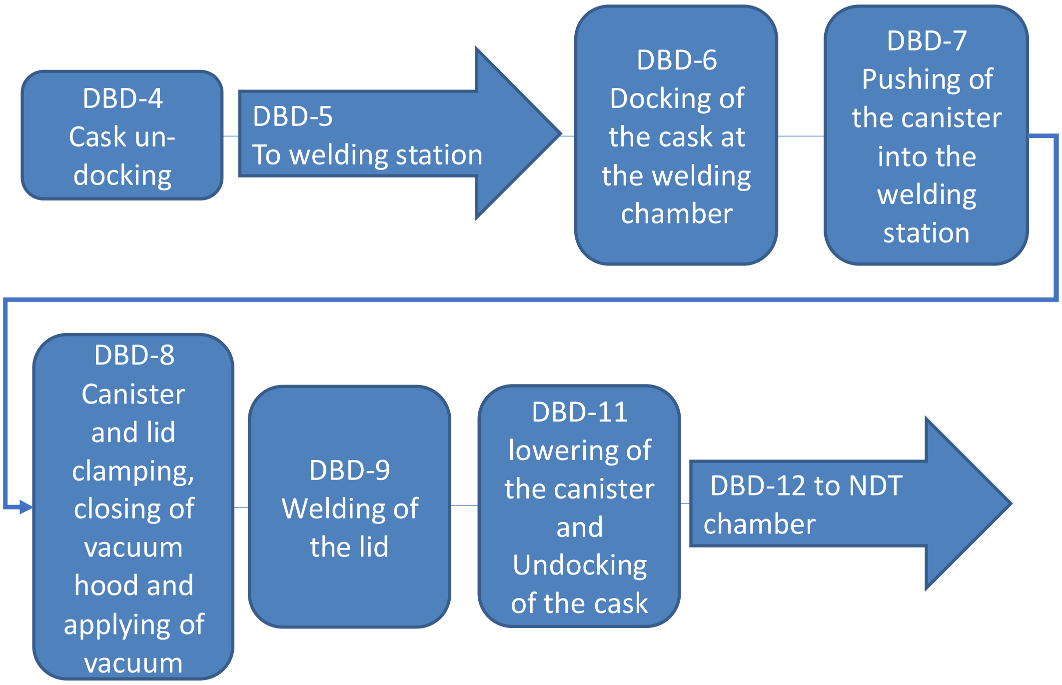


Figure 5-7: Process for the lid welding of the DBD-v1 canister

The canister transfer cask trolley is then moved from the fuel handling cell to the welding station (DBD-5). The transfer cask is then docked to the welding chamber (DBD-6), and the canister is pushed into the welding chamber (DBD-7). It is then necessary to centralize the canister inside the welding machine and to clamp the lid to the canister tube to ensure flawless welding. The vacuum hood can then be closed, and the necessary wrought vacuum can be applied (DBD-8). Then the lid is welded to the canister tube (DBD-9). After the welding, the vacuum hood is aerated again and opened, the clamp of the lid is released (DBD-10). The canister is then lowered back into the transfer cask, and the cask is undocked from the welding chamber (DBD-11). The canister is then transferred to the NDT chamber for testing (DBD-12). The subsequent process is shown in Figure 5-8.

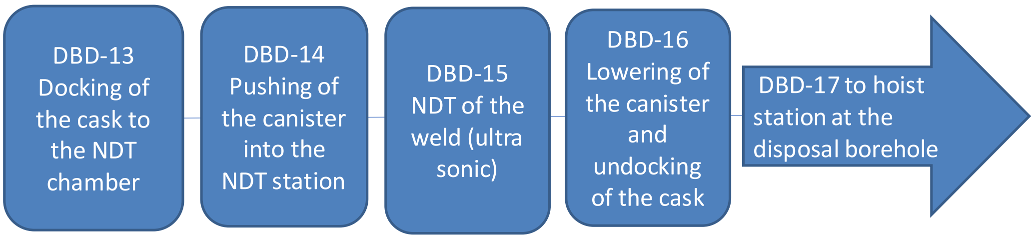


Figure 5-8: Processes for the NDT of the DBD-v1 canister

The transfer cask is at first docked to the NDT chamber (DBD-13), and then the canister is pushed into the NDT station (DBD-14). After that, the weld seam is tested with ultra-sonic testing (DBD-15). After testing, the canister is lowered back into the transfer cask, the lock sliders are closed, and the transfer cask is docked off from the NDT chamber (DBD-16). The tested canister can now be transported to the hoist station at the disposal borehole (DBD-17) for its disposal. The disposal process is depicted in Figure 5-9.

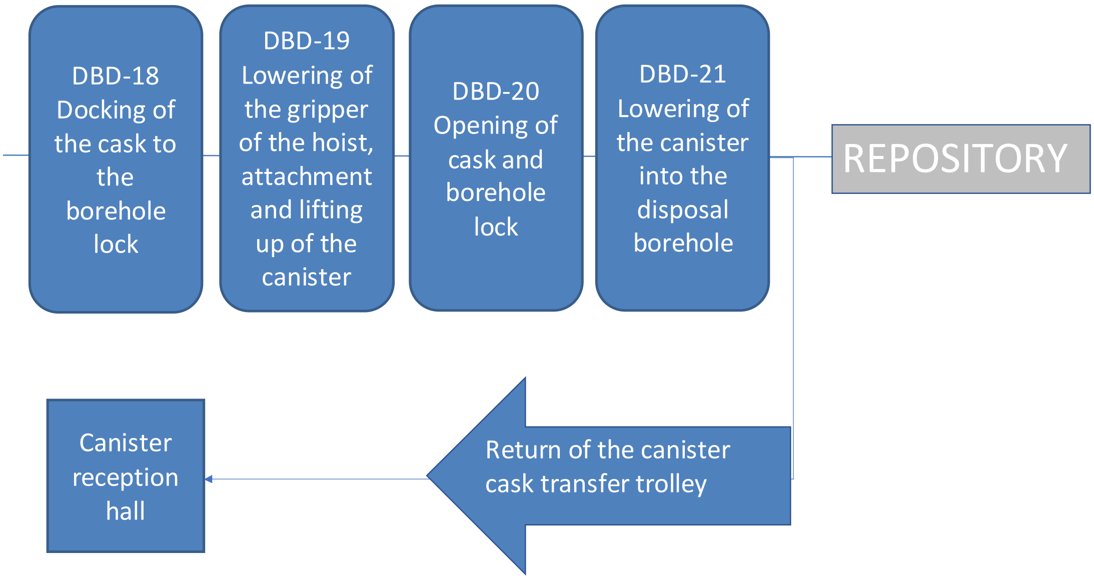


Figure 5-9: Processes for disposal of the DBD-v1 canister

After arrival at the disposal borehole, the transfer cask is first docked to the borehole lock (DBD-18). Then the upper cask lock is opened, and the grapple of the hoist is inserted and attached to the canister (DBD-19). Now the lower lock of the cask and the slider of borehole lock are opened simultaneously (DBD-20). The canister is then lowered into the disposal borehole and disposed of (DBD-21). After the grapple is retracted from the borehole and back in its starting position, the cask and borehole locks can be closed and the cask is docked off from the borehole lock. The canister cask transfer trolley is then returned to the canister reception hall and can be used for the next encapsulation and disposal cycle.

5.3.1 Properties of the DBD encapsulation plant

In this section, the necessary equipment for the different parts of the encapsulation plant for DBD-v1 canisters is described. The dimensions of the different rooms are also estimated.

Fuel handling cell:

For the fuel handling cell, the following equipment is estimated as necessary for the encapsulation process:

- Bridge or girder crane for all lifting purposes with a 10-tonne lifting capacity,
- Lock for the canister transfer cask,
- Lock for the spent fuel transport cask,
- Two contamination protection cones, one for the canister transfer cask and one for the spent fuel transfer cask,
- Tool for loosening of the screws of the spent fuel transport cask lid,
- Tool for taking gas samples out of the spent fuel transport cask,
- Cameras for process surveillance and for the check of spent fuel IDs,
- Measuring station for gamma measurement,
- Glove boxes or hand driven manipulators for taking of contamination samples and for emergency repairs (due to short operation time of the facility, no regular maintenance is foreseen).

The fuel handling cell should also have shielded windows for process surveillance. Access to the fuel handling cell should also be possible through a door or air lock. For installation of the equipment and maintenance, the door should allow access with machinery such as a forklift.

The dimensions of the fuel handling cell are estimated based on the size of Posiva's fuel handling cell (see Figure 3-5). The fuel handling cell of Posiva has a floor size of 8.4 x 13.2 square metres and a height of 8.2 metres. For the DBD-v1 fuel handling cell, the needed equipment is similar to the equipment shown in Figure 3-5. In the DBD-v1 fuel handling cell, no drying stations are necessary and only one place for gamma measurement is sufficient. Because of that, smaller dimensions of 7 x 10 metres for the fuel handling cell are estimated. The height of the fuel handling cell is reduced to 5 metres, this should be sufficient for the handling of fuel elements with a maximum length of 2.8 metres.

Welding chamber:

For the welding chamber, the following equipment will be necessary for the welding of the lid to the canister tube:

- Lock to dock on the transfer canister,
- Guiding tube to centralize the canister in the welding equipment,
- Clamping device to press the lid against the canister during welding,
- Customized electron beam welding machinery,

- Vacuum hood above the canister and the necessary pumps to apply the vacuum.

For the electron beam welding, a customized welding machine will be necessary. Usually the welding movement by electron beam welding is made by rotation or movement of the work piece. For the drive-through encapsulation process, it is not possible to rotate the canister while it is inside the transfer cask. So the welding equipment needs to be customized so that the welding gun can be rotated around the canister, which will require some engineering work.

For the welding chamber, it is expected that dimensions of 5 x 5 metres will be necessary. The height of the chamber is expected to be 3 metres. The welding equipment itself is estimated with a size of 2 m x 2 m and a height of 1 metres of the vacuum hood. The size is estimated according to Posiva’s former design of the electron beam welding chamber for the KBS-3 concept (Figure 5-10). Additionally, to the welding chamber itself, one auxiliary room for equipment such as the vacuum pumps and a control room are necessary.

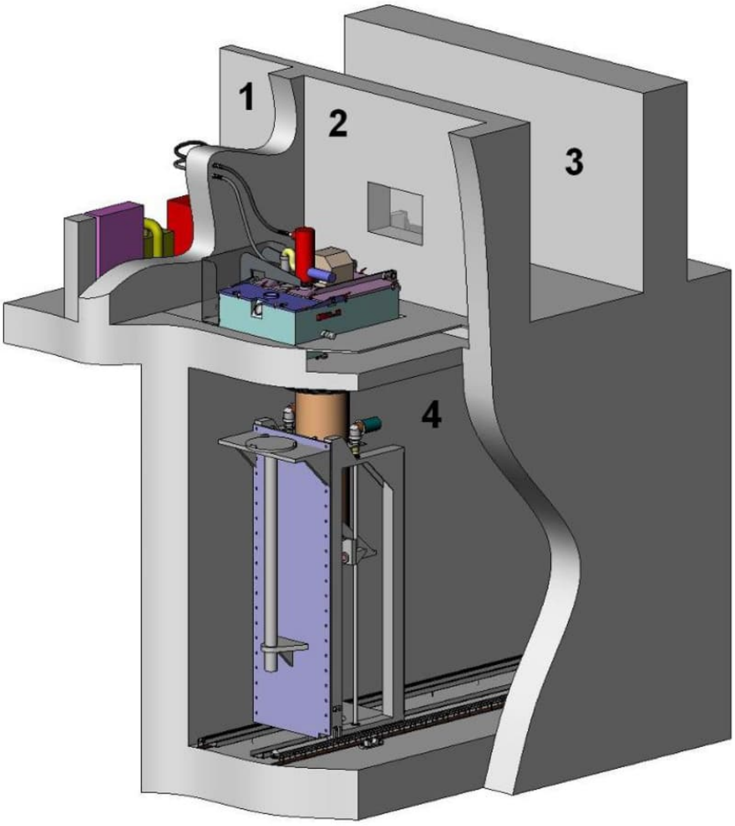


Figure 5-10: Cross-section of Posiva’s design of an electron beam welding chamber. Upper left to right: 1) room for auxiliary devices 2) welding room and welding machine 3) control room and 4) canister transfer corridor (Suikki 2008).

NDT chamber:

For the non-destructive testing chamber, the main equipment is the ultra-sonic testing device used for the test of the weld seam. Additionally, a lock to dock on the canister transfer cask is necessary.

The size estimate for the NDT chamber is similar to the welding chamber with a size of 5 m x 5 m and a height of 3 metres.

Shielded canister transfer trolley:

The shielded canister transfer trolley is used for the transport of the canister between the different stations of the encapsulation plant. Therefore, the following properties are necessary:

- Shielding of radiation and neutrons from the spent fuel,
- Compatibility to the transfer cask, described in Wunderlich et al. (2021),
- Ability to turn the transfer cask upright,
- Ability to raise and lower the cask for the docking procedures,
- Ability to push the canister inside the welding and NDT chamber.

In the German research project "Development of concepts for transportation and disposal of HLW containers (TREND)" (Bertrams et al. 2021), machinery for different German disposal concepts in different host rocks were designed. One device designed for German borehole disposal could be adapted to the needs of the DBD-v1 encapsulation plant. The device designed in TREND is a non-driven rail trolley that was planned as combined transport and disposal vehicle. It consists of a chassis connected to two bogies. Fixed to that is the turning mechanism for the integrated shielded cask. Spindle drives are used to raise or lower the transfer cask. All functions of the vehicle are powered with electric drives. Figure 5-11 shows the vehicle in the configuration for German borehole disposal.

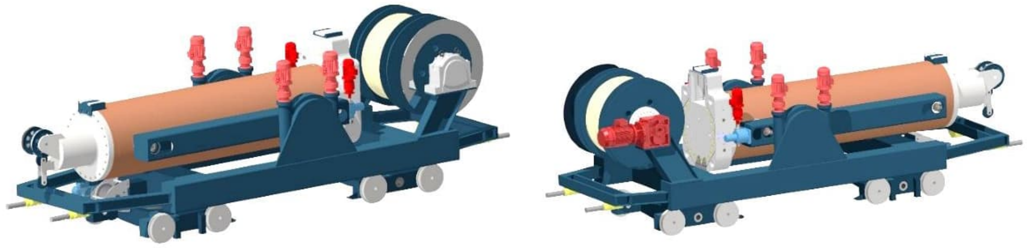


Figure 5-11: Shielded transport and disposal vehicle according to the German research project TREND (Bertrams et al., 2021).

For use of the vehicle in the DBD-v1 encapsulation plant, some changes are necessary. The hoisting drum on the rear end of the vehicle is not necessary for the encapsulation process and can be removed. Also, the pulley on top of the shielded cask can be removed. On its place, a lock-slider similar to the one shown on the bottom of the cask should be installed. The fixed shielded cask of the vehicle has the same properties as the transfer cask that was described in Wunderlich et al. (2021). The rail vehicle design has the advantage of automatic guidance so that the positioning of the vehicle below the locks of the different rooms in the encapsulation plant is easier. The vehicle is not able to do the pushing of the canister into the different chambers of the encapsulation plant, and it seems hard to integrate a piston for this function into the vehicle. The piston used for this purpose should possibly be integrated in the floor of the canister driveway. This has also the advantage that the positioning of the vehicle below the locks would be easier because the position of the piston would fix the vehicle position in all directions together with the tracks.

In the current design, the vehicle has a width of 3 metres, a length of roughly 10 metres, riding on a standard gauge track. With the cask tilted upright the maximum height is around 6.8 metres. The Norwegian spent fuel elements being significantly shorter than commercial fuel elements used in German power stations, the cask can be shortened for use in the DBD-v1 concept. The fuel elements being roughly two metres shorter than the commercially used fuel elements, it is expected that the maximum height of the vehicle will be around 5 metres.

5.4 Reutilisation of the encapsulation equipment

In the following, the reutilisation of the equipment of encapsulation plant relates to both disposal concepts unless specifically mentioned in the text.

Due to the short operational time, it is planned that the majority of the equipment from the encapsulation plant can be reutilised in either another nuclear waste disposal operation or in different industrial uses.

The equipment from the fuel handling cell can be disassembled and reassembled at a new site. To support the reuse of the fuel handling equipment it should be designed for easy decontamination so that it can be decontaminated and reused. At the moment it is expected that none of the equipment has to be treated as nuclear waste itself after the operation of the encapsulation plant is stopped. None of the equipment is planned to be embedded in the fuel handling cells concrete parts so that everything can be disassembled. In the end, only the concrete walls, floors and ceiling from the fuel handling cell are left and can be demolished. The fuel handling cell equipment is especially designed for the needs of a nuclear waste handling operation. Therefore, it is likely that reuse of the equipment in non-nuclear applications is not useful.

The equipment necessary for the electron beam or friction stir welding process, mainly the welding machine itself and the equipment for applying the vacuum, can also be disassembled and reused in another nuclear waste disposal operation elsewhere. Furthermore, the welding equipment will not be contaminated, and even though it is customized to the corresponding canister type, it can also be used in non-nuclear applications that require high quality welding, such as the aerospace industry.

The equipment for the non-destructive testing of the weld seam is also reusable. The equipment is customised for the test of the canister, but it still could be used in a widespread of other industrial applications that require ultrasonic testing of weld seams or material properties.

Reuse of the DBD-v1 canister transfer trolley in a similar encapsulation operation to the Norwegian one is also possible. The trolley itself can be disassembled, shipped and reassembled at another site without problems. For use in the German disposal concepts, the trolley was designed for easy assembly because it was planned to be transported into the mine in parts due to the transport via a shaft. The trolley itself is specially designed for the purposes inside the spent fuel encapsulation plant. Therefore, it seems highly unlikely that a use outside of the nuclear industry can be found after the Norwegian facility is closed.

5.5 The main differences in the processes

The main differences of the two presented encapsulation processes are presented in the table below.

Table 5-1. Main differences between KBS-3 and DBD encapsulation processes.

Process component	**KBS-3**	**DBD-v1**
Canister	Dual structure, with cast iron insert and copper shell; two lids: inner steel lid and outer copper lid	Single structure, canister made of austenitic steel with one lid
Canister transfer trolley	Specially designed trolley with lifting table, rotation function and lid lifter	Specially designed transfer trolley for the canister transfer cask. No rotation of the canister is needed, but the vertical movement of the canister is enabled with a piston.
Radiation protection	Canister transfer corridor must be remotely operated because of the radiation	Operations can take place in the canister transfer corridor during encapsulation process
Fuel handling process	Gas exchange, inner lid	Only one lid, no gas exchange
Lifting equipment	Canister has more weight, which has to be taken into account with the lifting capacities	
Welding process	Friction stir welding	Electron beam welding
Machining of the weld	Needed	Not needed
NDT inspection	Ultrasonic, eddy current, visual	Ultrasonic, visual

5.6 Layouts of the encapsulation plants in Norway

5.6.1 Facility layout for KBS-3

Illustration of the KBS-3 encapsulation plant placed on the surface layout of the National Facility (Ikonen et al. 2020) is shown in the figure 5-12. The plant (#21) covers an area of about 1700 m^2 (35 m x 49 m) with a volume of about 40 500 m^3. It should be noted, however, that the surface lay-out and buildings were originally planned without an encapsulation plant and therefore the illustration only shows the size of the encapsulation plant in relation to other buildings. Encapsulation plant layouts for the KBS-3 canister are annexed at the end of the report in Section 11.1.

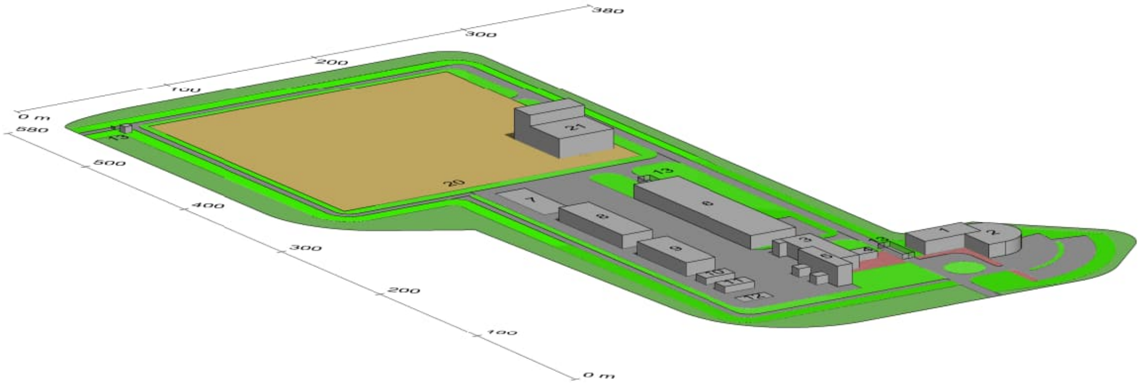


Figure 5-12 Surface lay-out of the National Facility with the KBS-3 encapsulation plant (#21).

5.6.2 Facility layout for DBD-v1

Illustration of the DBD-v1 encapsulation plant placed on the surface layout of the National Facility (Ikonen et al. 2020) is shown in the figure 5-13. The plant (#21) covers an area of about 1100 m^2 (26 m x 41 m) with a volume of about 20 000 m^3. Correspondingly to the KBS-3 surface layout, the illustration only shows the size of the encapsulation plant in relation to other buildings. Encapsulation plant layouts for DBD canister are annexed at the end of the report in Section 11.2.

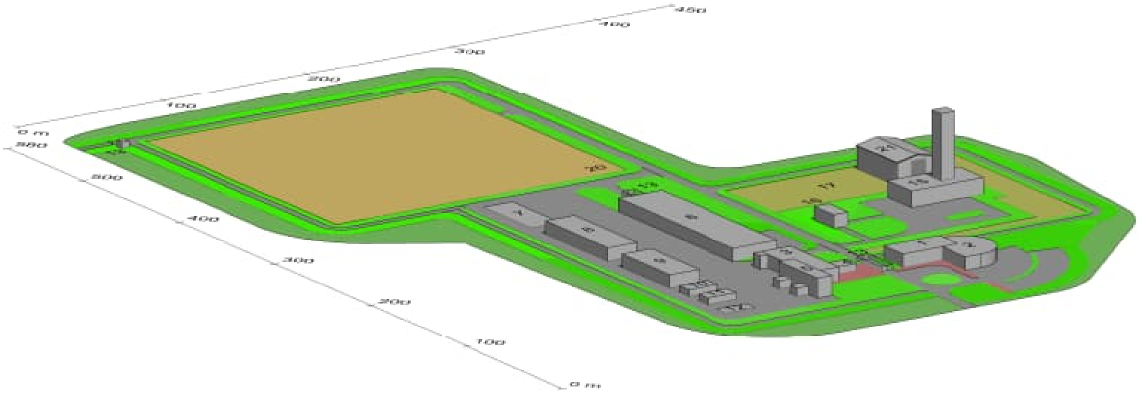


Figure 5-13 Surface lay-out of the National Facility with the DBD-v1 encapsulation plant (#21).

6 FACILITY OPERATION

6.1 Human resources and facility output

The estimated number and type of personnel needed in the KBS-3 and DBD encapsulation plant is presented in Table 6-1. It is noted that the estimation is for direct work force envisaged at the plant. Overlapping operations of the plant have been taken into account in the estimation, like simultaneous reception of the disposal canister and the transport cask of the spent fuel which would need different workers for these tasks. It has also been assumed that different operations of the process (fuel handling, welding, machining and NDT inspection) require specialised expertise. On the other hand, much of this expertise can be outsourced and needs not to be recruited in-house. Outsourcing of the human resources can also be justified by the short operation time of the encapsulation plant.

Table 6-1. Personnel needed for the encapsulation plant.

Function	Number of personnel
Chief operation manager	1
Canister reception	1
Transport cask reception	1
Fuel handling cell	1
Welding	1
Machining	1
NDT inspection	1
Safety & radiological protection	2
Transport	2
Licensing	1
Requirements management	1
Total	13

The theoretical output of the encapsulation plant is largely based on the trajectories of the process equipment of the plant (cranes, transfer trolleys, fuel handling machine, etc.), which involve vertical and horizontal movements of the canister. The most time-consuming part of the process is the fuel transfer in the fuel handling cell. In total, it can be estimated that encapsulation of one KBS-3 canister would take 3-4 working days. For DBD it is estimated that a canister per day could be encapsulated.

6.2 Maintenance

For its fuel handling cell, the Finnish Posiva plans to do maintenance only in five-year cycles (Suikki, 2013). For the Norwegian case with a shorter operational time (from 6 months to 2 years), it is therefore expected that the equipment of the fuel handling cell can endure the whole operational period without the need of major maintenance. Therefore, it is expected that no further equipment for maintenance purposes needs to be held available. Maintenance would only be necessary in the case of major equipment breakdowns, which can be prevented by fail safe equipment design. In this case, maintenance means stopping of the spent fuel encapsulation process and decontamination of the whole fuel handling cell so that workers can enter it and make major repairs or exchange the equipment.

After all the Norwegian spent fuel is encapsulated, the facility will be put out of operation, cleaned and decontaminated and disassembled. The reuse of the equipment of the encapsulation plant was discussed previously in Section 5.4.

For a longer operational period than currently expected, it is advised that the facility runs in operational cycles of five years, corresponding to the maintenance cycles of Posiva, and the facility operation is then stopped for a period of preventive maintenance. Preventive maintenance means that equipment and facilities are checked and serviced in a planned manner. Here it should be done in scheduled cycles to prevent the breakdown of equipment inside the encapsulation plant. In this preventive maintenance period, the fuel handling cell should first be cleaned and decontaminated so that workers can enter it. Then the installed equipment should be checked for wear or damages, and wear parts should be replaced.

7 COSTING OF THE ENCAPSULATION PLANTS

The aim in this chapter is to evaluate whether the differences in the encapsulation plant costs are different for DGR and DBD to such extent that it could inform a decision on DGR versus DBD. Estimates introduced in this chapter are very rough because of very early design stage of the encapsulation plants.

Costs are estimated based on experience from nuclear waste management projects in many countries including Finland, Sweden, Czech Republic and South Korea.

All costs are estimated and presented in euros. The prices do not include the value-added tax (VAT). It should be noted that the price level in Norway may differ from the price level in the reference countries.

The cost level is 1/2021. The interest rate of the money has not been taken into account.

Owner costs are included in the investment costs. Owner costs are assumed to be 15% of the investment costs. Also contingencies for unspecified costs are included in the costs. Contingencies are high because of the very early design phase of the facility. 40% contingency is estimated in this phase for both alternatives.

Costs for the encapsulation plant are assumed to consist of two parts:

- Construction costs = building itself. This includes construction of all structures for the building and the systems that the building will need whatever the use of the building would be. For example, normal ventilation, lightning, electricity etc.
- Process systems and equipment costs. This includes all systems and equipment that are needed because this building will be used for the encapsulation of the spent fuel. For example, processes of the fuel handling cell and transfer of the canister in the encapsulation plant.

Construction costs are estimated by using existing reference data and assuming that construction costs per volume of the building would be the same for different encapsulation plants. Construction costs (EUR/m^3) for weather shelter warehouse in the DBD encapsulation plant have been assumed to be half of the corresponding construction costs for other parts of the encapsulation plant. Having information about reference plants and planned volume for KBS-3 encapsulation plant and DBD encapsulation plant, corresponding construction costs for KBS-3 encapsulation plant and DBD encapsulation plant can be estimated. Encapsulation plant concepts are presented in the Chapter 5.

Costs for the process systems and equipment are estimated by using reference data and current information about what kind of systems and equipment are needed for 1) KBS-3 encapsulation plant and for 2) DBD encapsulation plant.

Number of the canisters for NND spent fuel will be very small, about 30 for DGR concept or about 90 for the DBD concept. If the differences in the canister costs would be within 0 – 200 000 euros / canister, still the total difference in the costs would be some millions of euros rather than tens of million euros. Therefore, it is estimated that the costs of the canister manufacturing will not differ to such an extent that it could inform a decision on DGR versus DBD. Research and development of the canisters are discussed in the Chapter 2.

Dismantling costs include typically removal and transfer of the structures that have been constructed and installed for the encapsulation plant. Generally, all the structures will be removed after operation period. Costs for dismantling of the structures could be estimated to be 30% of the construction costs of buildings and structures and 5% of the investment costs for equipment, installations, HVAC and electricity. It is possible that some equipment could be sold and recycled. Differences in the dismantling costs between the alternatives are minor and not discussed here. Demolition of the plant will generate some radioactive waste, in the order of 100 m^3 could be estimated in this design phase.

7.1 Encapsulation plant for KBS-3 canisters

Estimated investment costs for the encapsulation plant for KBS-3 canisters are about 100 MEUR. Cost estimation is presented in Table 7-1.

Table 7-1. Investment costs for the encapsulation plant for KBS-3 canisters.

Construction costs		28	MEUR
Fuel handling systems, cranes and lifts	16		MEUR
Process systems	9		MEUR
Automation and telecommunication systems	6		MEUR
Electric power systems	5		MEUR
Process systems and equipment		36	MEUR
Sub-total		64	MEUR
Owner costs, 15%		10	MEUR
Sub-total		74	MEUR
Contingency for uncertainties, 40%		29	MEUR
Total		103	MEUR

7.2 Encapsulation plant for DBD canisters

Estimated investment costs for the encapsulation plant for DBD canisters are about 60 MEUR. Cost estimation is presented in Table 7-2.

Table 7-2. Investment costs for the encapsulation plant for DBD canisters.

Construction costs		12	MEUR
Fuel handling systems, cranes and lifts	11		MEUR
Process systems	8		MEUR
Automation and telecommunication systems	5		MEUR
Electric power systems	3		MEUR
Process systems and equipment		27	MEUR
Sub-total		39	MEUR
Owner costs, 15%		6	MEUR
Sub-total		45	MEUR
Contingency for uncertainties, 40%		18	MEUR
Total		63	MEUR

7.3 Research and development

Encapsulation process and plant for the KBS-3 canister are more developed and tested than the corresponding process and plant for the DBD canister. Correspondingly also the level of technical maturity for DBD concept is not comparable to the KBS-3 concept. It could be very roughly estimated that few tens of million euros more for the research and development would be needed for DBD encapsulation than for KBS-3 encapsulation.

Research and development for the concept and long-term safety assessment is not discussed here since this report concentrates in the encapsulation plant.

7.4 Summary

In this very early design phase, it can be estimated that costs for the encapsulation plant for the DBD canister will be lower than costs for the KBS-3 encapsulation plant. The difference is estimated to be in the order of 40 MEUR.

Since the level of technical maturity for the DBD canister and DBD encapsulation is lower than for the KBS-3 canister, more research and development is needed for the DBD alternative. Costs for this research and development have been estimated to be lower than the differences in the investment costs.

Finally, the differences in the costs for the encapsulation for the DGR and for DBD seem to be some tens of millions of euros. Differences in the other components will probably be larger, and the encapsulation will, therefore, not affect the decision between the DGR and DBD, or at least the encapsulation will not be the most important topic in the comparison.

8 REVIEW OF POTENTIAL ENCAPSULATION PLANTS IN EUROPE

The post-conditioning programme as well as the corresponding facilities are always tailored to the waste form and DGR (deep geological repository) conditions in the actual nation where the waste is to be disposed of. Both the waste form and the disposal waste package represent two components of the engineered barrier system. While the waste form is mostly predefined, the package design is adapted to the disposal concept. Today, no repositories for HLW or SNF (spent nuclear fuel) is in operation. Therefore, no post-conditioning facility or encapsulation plant is in operation either. However, within the next decades it is expected that across Europe several repositories and post-conditioning facilities will start operation. Table 8-1 and Figure 8-1: give an overview to the status of different international disposal programmes and the intended start of operation.

Table 8-1: Overview of international rad waste management programmes.

Nation	Concept, status and schedule
Finland	Disposal of SNF in KBS-3 canisters in crystalline host rock DGR under construction Operation of DGR and encapsulation plant planned for 2025 (trial run 2023)
Sweden	Disposal of SNF in KBS-3 canisters in crystalline host rock In licensing Operation of DGR and encapsulation plant planned around 2030
Switzerland	Disposal of SNF in cast iron canisters in claystone Final decision for site selection in 2024 Start of operation DGR and encapsulation plant between 2050 to 2060
Czech Republic	Disposal of iron-based canisters in crystalline host rock On-going site selection Start of operation around 2065
Germany	On-going site selection (until 2031) Host rock not yet known (salt, claystone and crystalline as options) Disposal concept and waste package concept not yet known SNF and HLW
France	Disposal of HLW in a steel based overpack in claystone In licensing Industrial pilot phase in late 2020s Start of operation afterwards (around 2038)
Belgium	Disposal of SNF and HLW in supercontainers (concrete) in clay Site selection not yet started, formal decision of the government is missing (no schedule)
UK	On-going site selection, no fixed schedule Host rock not yet known (salt, claystone and crystalline as options) Two waste package concepts existing: copper mantled and cast iron SNF and HLW

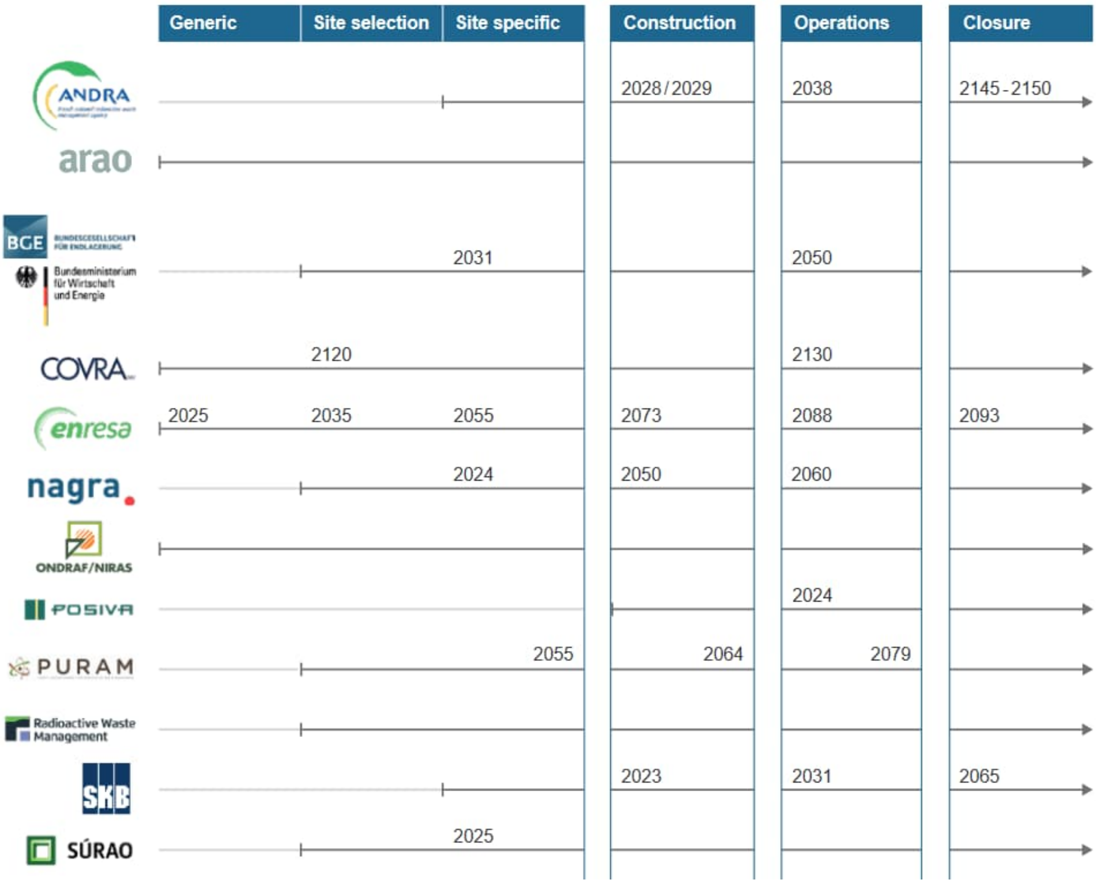


Figure 8-1: Overview of European DGR maturity, based on (IGD-TP, 2020).

The examples illustrates that the Scandinavian countries Sweden and Finland are close to operation. Both use the KBS-3 concept. If NND focuses on the deep geological repository with KBS-3 concept, then the encapsulation would be similar in all three countries. From the technical point of view, encapsulation in the projected plants (Sweden or Finland) is possible. If the DBD concept is favoured, the technical feasibility of encapsulating the waste in both facilities is lost. The differences in both encapsulation processes are too large to combine them in one facility (e.g. different welding technique).

In the same way, the situation can be described for other nations. So far, none of them has determined the KBS-3 concept. For the UK, the application of a KBS-3 type concept within crystalline rock (“higher strength rock” in UK wording) represents one option beside others. In Germany, KBS-3 type concepts are under discussion. However, for both countries no decision is made and a prediction is not possible.

For all the other examples/nations, the differences within the actual waste package concept seem to be too large to allow the handling of Norwegian waste streams and encapsulation within their future facilities. This statement applies to both the KBS-3 and the DBD concept. Relatively high similarities exist between the Swiss cast iron waste package and the DBD canister as well as with the Czech iron canister and the DBD canister. However, even if the general encapsulation process is the same, the differences in dimension and material of the canisters would require a certain kind of reconstruction of the encapsulation plant. Today, the actual effort cannot be determined exactly. A high uncertainty is, therefore, detected, and the possibility of technical comparability is assessed to be very low.

For completeness, it should be highlighted that in Germany a pilot post-conditioning plant was built at the Gorleben interim storage facility. The pilot plant was designed to demonstrate the dismantling of PWR spent fuel assemblies into fuel rods and structural parts. Afterwards the rods were placed inside so-called POLLUX® casks. Furthermore, the facility, which was designed as a multi-purpose facility, could also carry out other work due to its technical facilities, such as maintenance and inspections of all types of transport and storage casks (in Germany, mainly types of the CASTOR® family). The facility was constructed but never tested under “hot” conditions. In the future, the use of this facility is not very realistic in the German HLW disposal programme. Firstly, it is not yet decided that the future HLW/SF repository use the POLLUX® concept as well as dismantling of the SF assemblies. Secondly, the Gorleben site is today excluded as a potential site because of the updated safety requirements given by the German Site Selection Act. Finally, the facility was constructed in the early 1990s, never updated and does no longer represent the state of the art. (BGZ, 2021)

Figure 8-2: German pilot post-conditioning plant at the Gorleben site (left), view into the fuel handling cell (right above) and buffer storage POLLUX® cask (right below), based on (BGZ, 2021)

The examples show that such post conditioning facilities are currently not available. Comparable facilities to handle SF/HLW and encapsulate these can be found in the nuclear industry. Available reprocessing and recycling services for spent nuclear fuel from research reactors were documented by the IAEA, see e.g. (IAEA, 2017).

Commercial large-scale applications are known from reprocessing. Such facilities offer the service of reprocessing of spent fuel and treatment and encapsulation of radioactive waste to other nations. The number of reprocessing facilities in operation in Europe is limited. Sellafield (UK) and La Hague (France) can be highlighted.

Sellafield (UK) represents a nuclear industry complex with several different facilities. The area includes a vitrification plant, a fuel assembly factory as well as reprocessing plants for British Magnox reactors, AGR reactors and foreign LWR reactors, for instance. Reprocessing includes the extraction of the individual component parts of plutonium, uranium and waste. The so-called THORP facility (Thermal Oxide Reprocessing Plant), operated by the state-owned Sellafield Ltd, stopped reprocessing in 2018 after fulfilling the last contracts.

The facility in La Hague is today operated by Orano. *“Orano Group is the world leader in the recycling of used nuclear fuel from reactors worldwide. Orano la Hague offers services for recycling radioactive materials for reuse in new nuclear fuel.”* (ORANO, 2021)

The facility, originally intended for reprocessing plutonium for military applications, continues today reprocessing for civil/commercial applications and offers services for several costumers across Europe. During the last decades, several countries, e.g. Germany, Belgium, Switzerland, the Netherlands and Ukraine, joined into contracts for reprocessing of LWR spent nuclear fuel. Different plants were constructed during that time. The so-called UP3 plant represents the latest expansion stage. The facility was designed for reprocessing of uranium oxide fuel initially enriched to 3.25% in ^{235}U, with a burnup of 33 GWd/tU and cooled for three years. However, the La Hague site is authorized, based on supporting studies, to reprocess other types of fuel as well. *“SNF of gas cooled reactors, fast breeder reactors, pressurized water reactors (PWRs) and all types of aluminium cladding for MTRs* (Materials Testing Reactor) *are included in the authorization decree.”* (IAEA, 2017)

For SNF from research reactors, different types of fuel can be handled. Based on (IAEA, 2017), reprocessing technology is in general available for SNF types of U-Al, U-Si, UO_2, U-Mo and U-Zr. The reprocessing can be summarized into four major steps:

1. Interim storage and cooling at the site
2. Dissolution in hot nitric acid solution
3. Extraction of uranium and plutonium from the solution in several cycles
4. Stabilization of the remaining (fission products and minor actinides) in a glass matrix and return to the customer

The La Hague site is used to handle foreign waste and reprocess it. In general, the technical fundamentals to handle the Norwegian waste are available, even if a reprocessing is not intended. The most significant differences between common reprocessing steps and encapsulation are represented by the welding of the waste package. Reprocessed waste will be shipped in transport and storage casks back to the owner state. Such casks are not welded because they are used only for transport and interim storage. In contrast, a waste package has to be welded at site and then transported back. Welding equipment specialized in KBS-3 or DBD canisters does not exist at the site and has to be installed.

However, in addition to the usual customer–supplier commercial and industrial relationship, intergovernmental agreements between the Government of France and the corresponding State are necessary. *“Projects for reprocessing and recycling research reactor SNF have to be anticipated, in accordance with French and international laws that guarantee the safety and security of operations. Anticipation between AREVA and its customers is also needed in drawing up the reprocessing plan of their SNF.”* (IAEA, 2017)

There are currently facilities in Europe that handle nuclear fuel elements. However, none of the operational ones have existing encapsulation processes in place. If NND considers KBS-3 canister then the planned facilities in Sweden and Finland could technically handle the process – with some modification (e.g. if Norway uses different fuel transport cask). However, using one of the existing fuel handling facilities for NND’s purposes would require addition of such equipment and machinery to an existing one. Furthermore, using an existing international facility for encapsulating NND’s HLW would require additional bureaucratic effort for transporting HLW across national boundaries. There would be also additional effort in transporting empty canisters to an international site, and then transporting filled canisters back to NND’s site. Moreover, it is possible that several transfer casks would be needed to perform the disposal operation in the envisaged short time frame.

The effort and cost of such additions would be of similar magnitude as in building an encapsulation facility at NND’s own site.

9 CONCLUSIONS AND RECOMMENDATIONS

Manufacturing of two canister types and their feasibility for encapsulation of Norwegian spent nuclear fuel have been studied in this report. In terms of technical development, the DBD-v1 canister is still in its infancy, and no industrially manufactured prototype has been made yet of this specific design. Nonetheless, the planned manufacturing methods for DBD-v1 canister are industry standards suggesting that only some customization of the available equipment would be needed for the manufacturing process.

For the KBS-3 canister, R&D has been done over four decades, and first canisters containing spent nuclear fuel are planned to be disposed of in Finland in the coming years. With some modifications to the canister length and canister insert, the canister would be available for encapsulation of Norwegian spent nuclear fuel.

The encapsulation of Norwegian spent nuclear fuel can be streamlined, considering the size of the fuel inventory, the geometry of the fuel assemblies and the source term. Comparing to the planned encapsulation of spent nuclear fuel in Finland and Sweden, the Norwegian process is considered simpler and the encapsulation plant smaller than in the reference countries.

Based on the streamlined encapsulation processes and derived encapsulation plant designs, this study suggests that the encapsulation based on the DBD concept costs roughly 40 M€ less than the encapsulation with the KBS-3 concept. Considering the lower technical maturity of the DBD encapsulation and the R&D investment required, the differences in the costs of the DBD and the KBS-3 encapsulation seem to be some tens of millions of euros. Consequently, the choice between two alternative concepts cannot be demonstrated by the differences of the processes and costs, or at least the encapsulation will not be the most important topic in the comparison of two disposal concepts.

International encapsulation services are currently not available although several companies have technologies to operate with spent nuclear fuel, especially for reprocessing purposes. However, they do not have equipment and systems for encapsulation of spent nuclear fuel for disposal. The effort and cost of such additions could be of similar magnitude as in building an encapsulation facility at NND’s own site.

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11 ANNEX

11.1 ANNEX: KBS-3 layouts

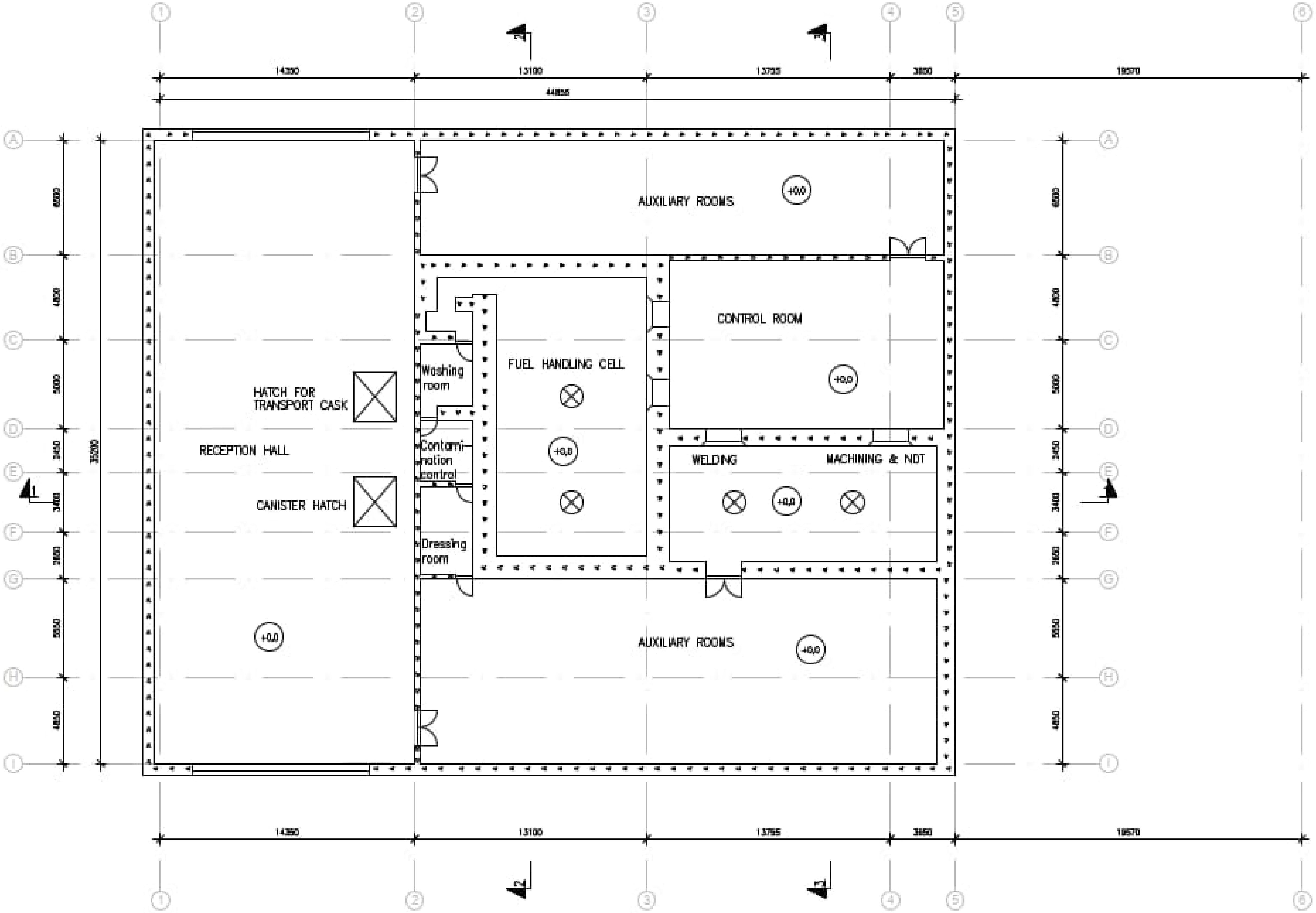

Figure 11-1 KBS-3 layout +0,0 m

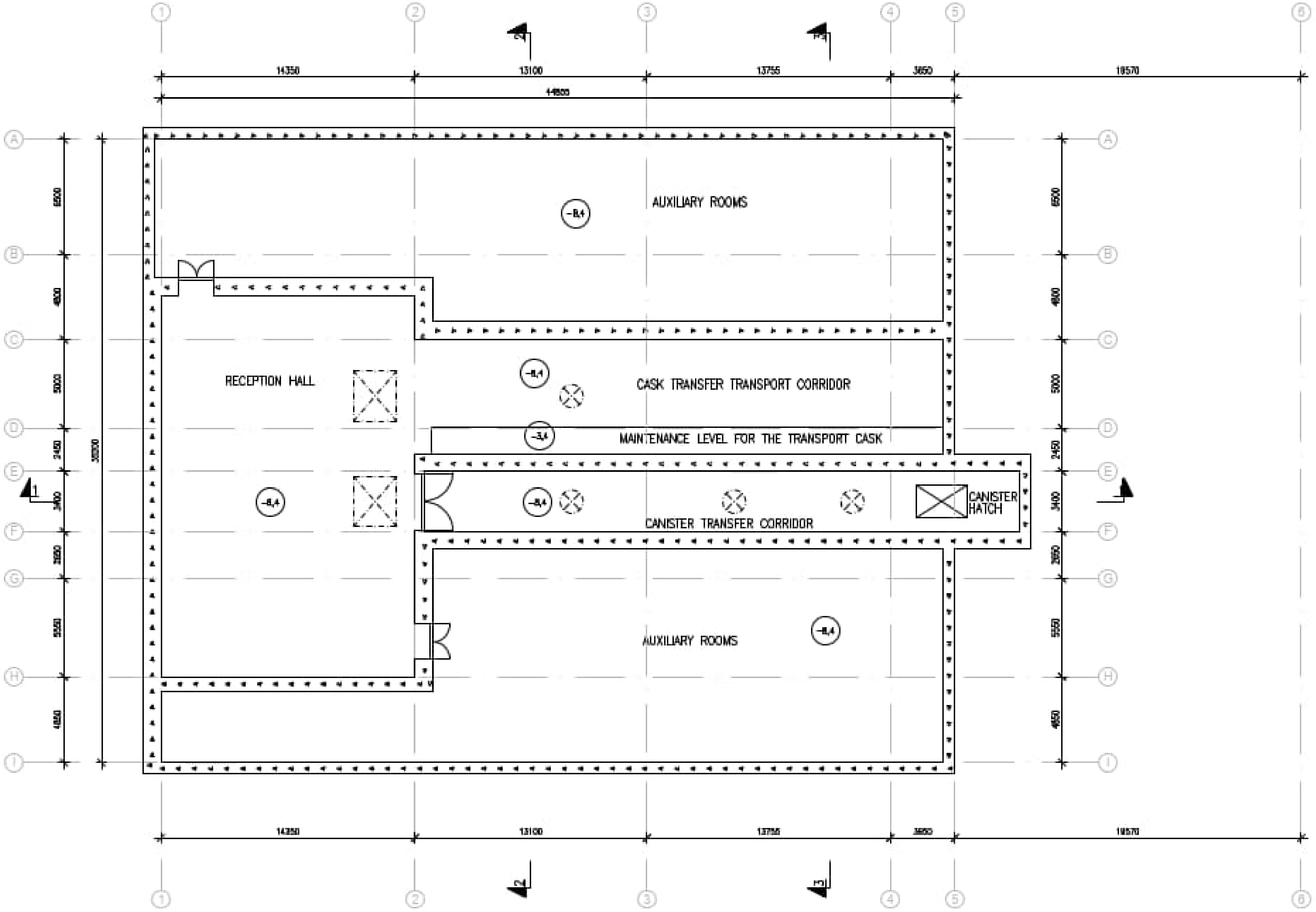

Figure 11-2 KBS-3 layout -8,4 m

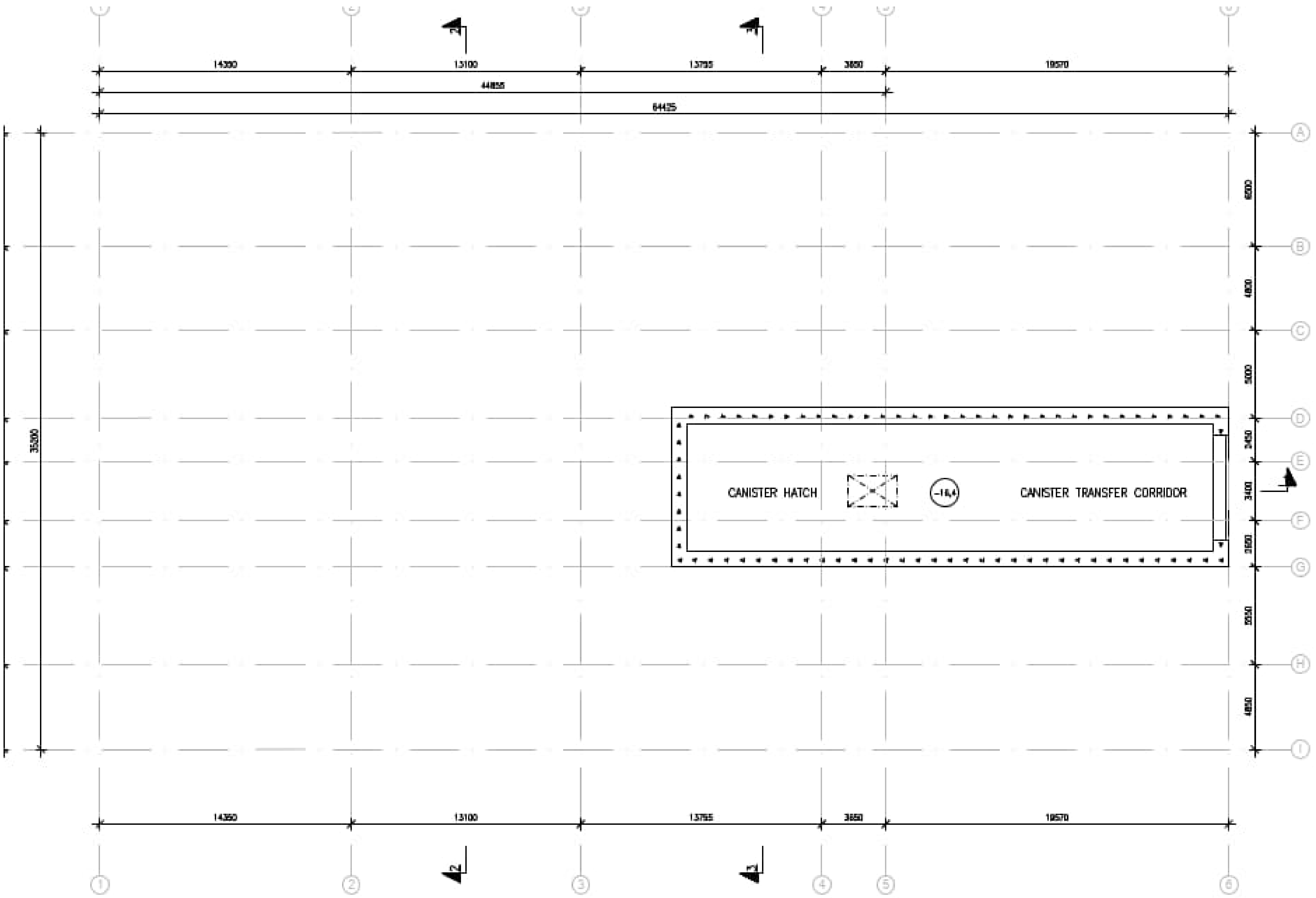

Figure 11-3 KBS-3 layout -16,4 m

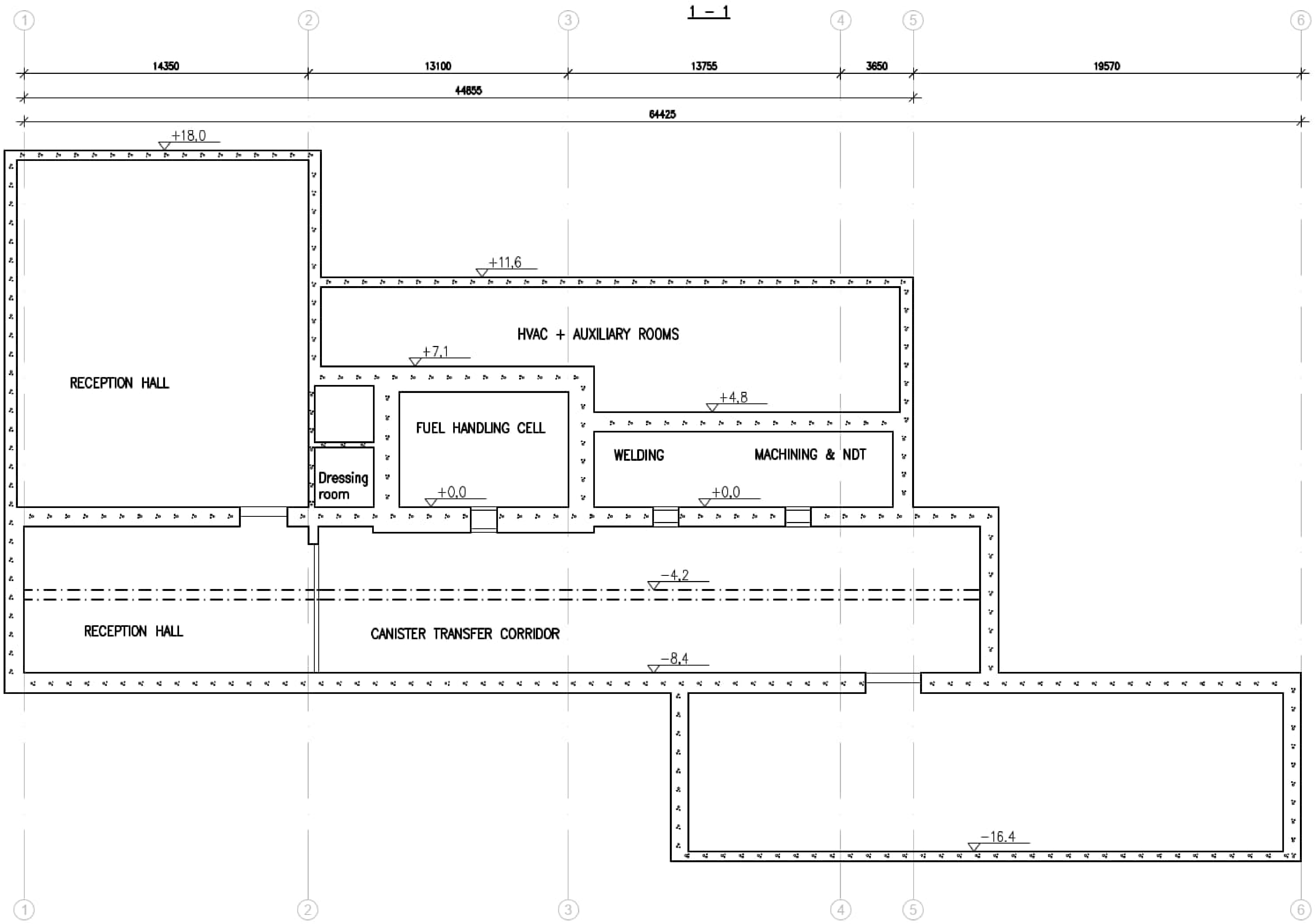

Figure 11-4 KBS-3 section 1-1

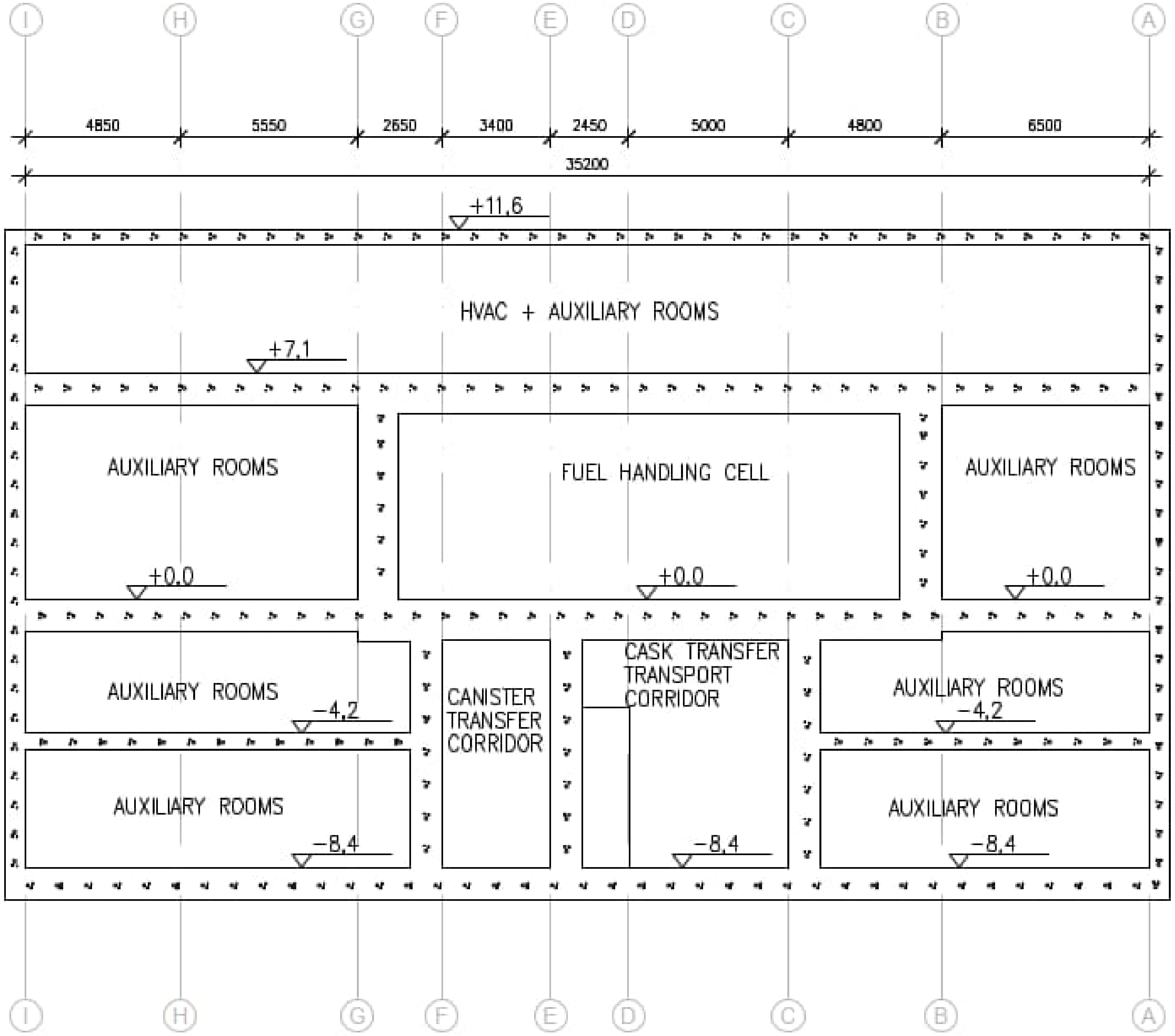

Figure 11-5 KBS-3 section 2-2

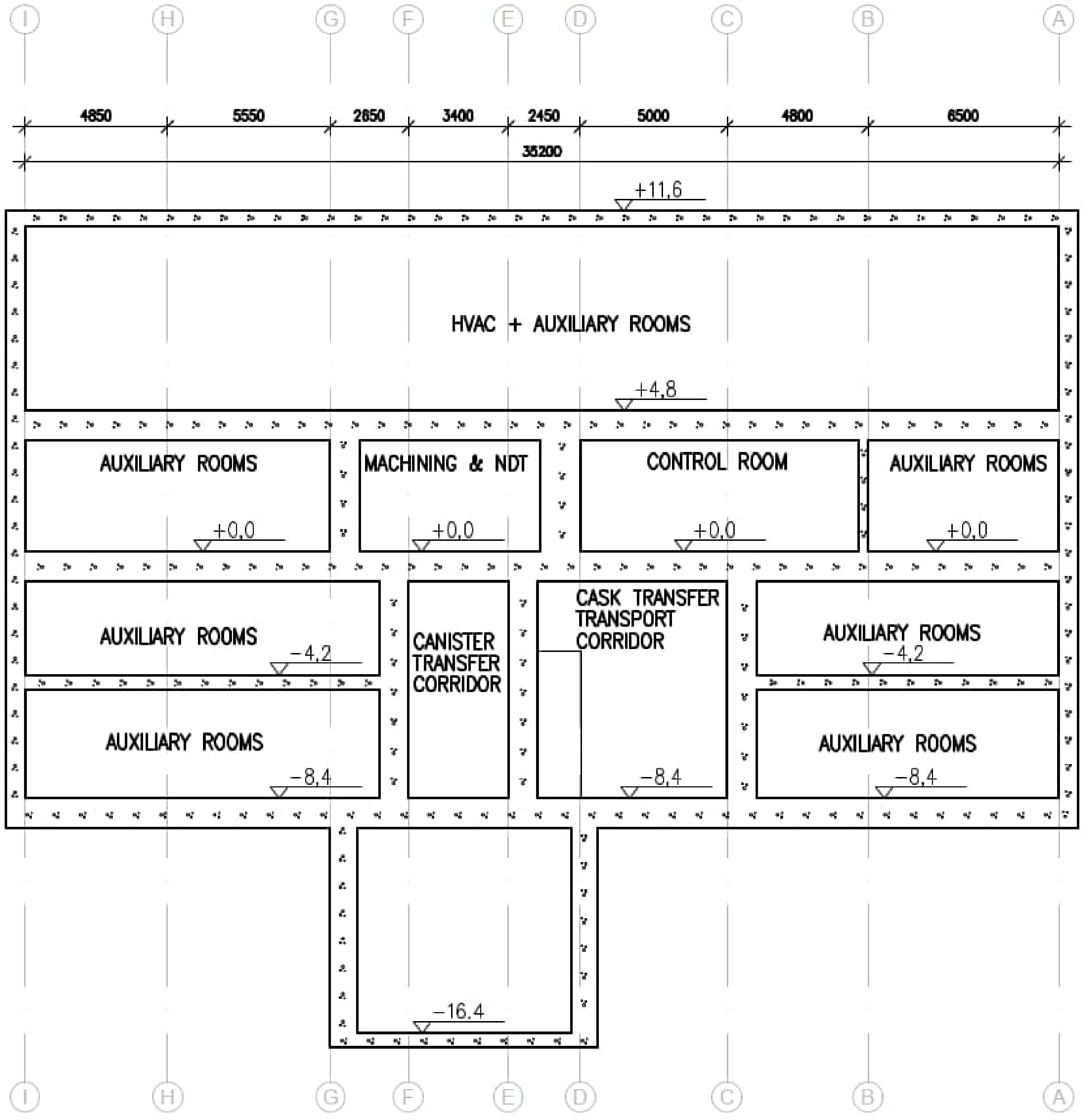

Figure 11-6 KBS-3 section 3-3

11.2 ANNEX: DBD layouts

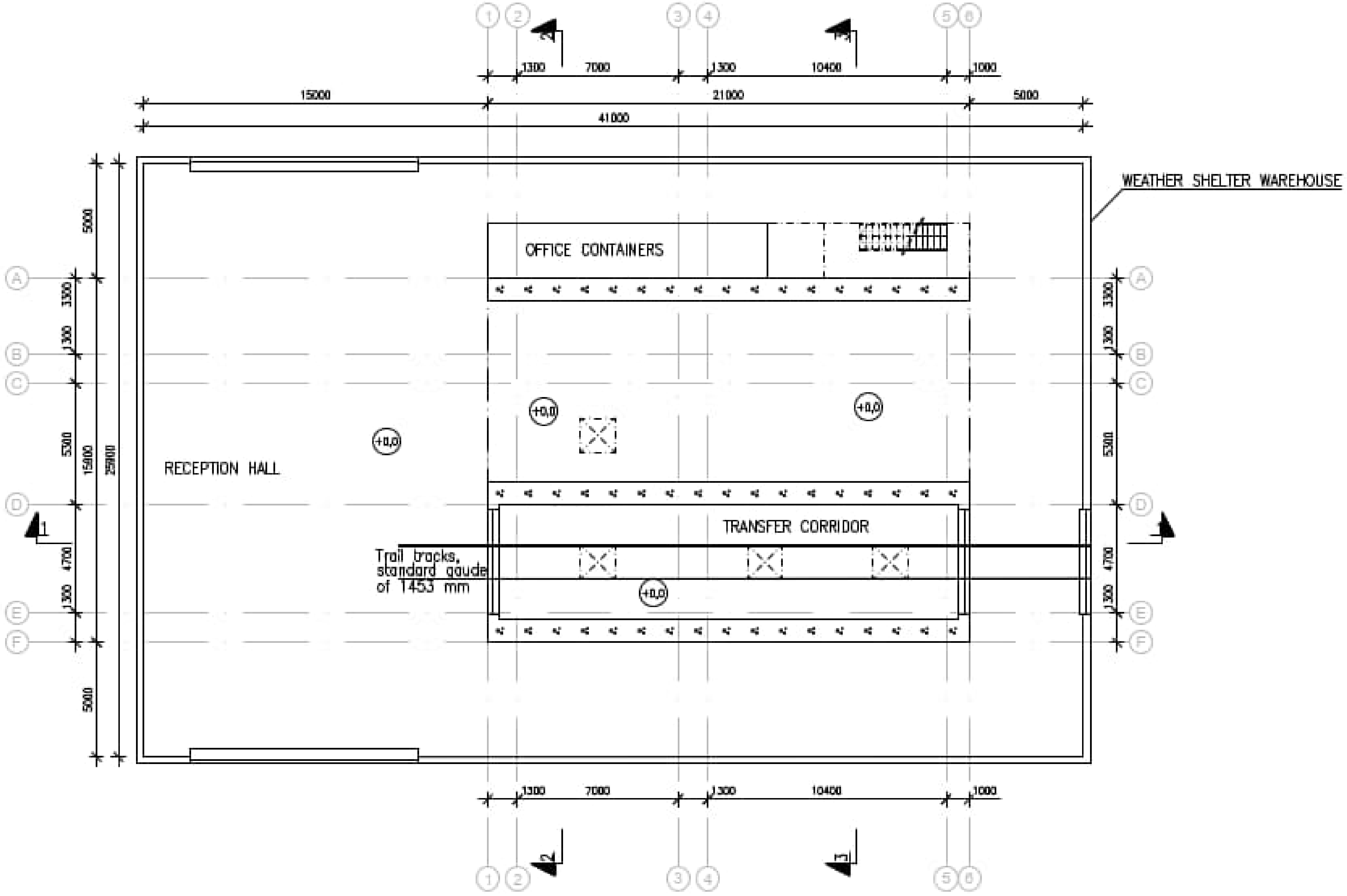

Figure 11-7 DBD layout +0,0

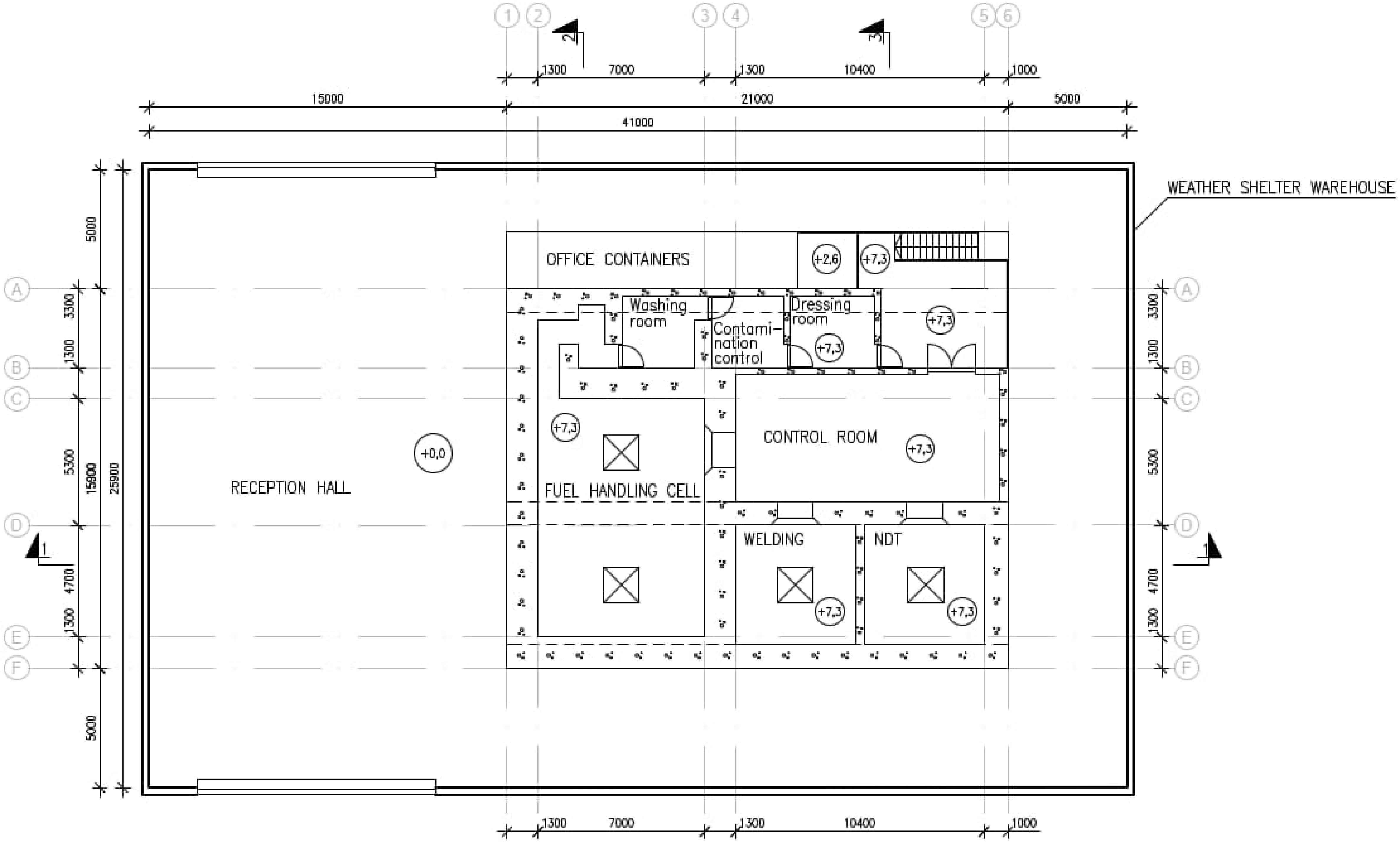

Figure 11-8 DBD layout encapsulation level

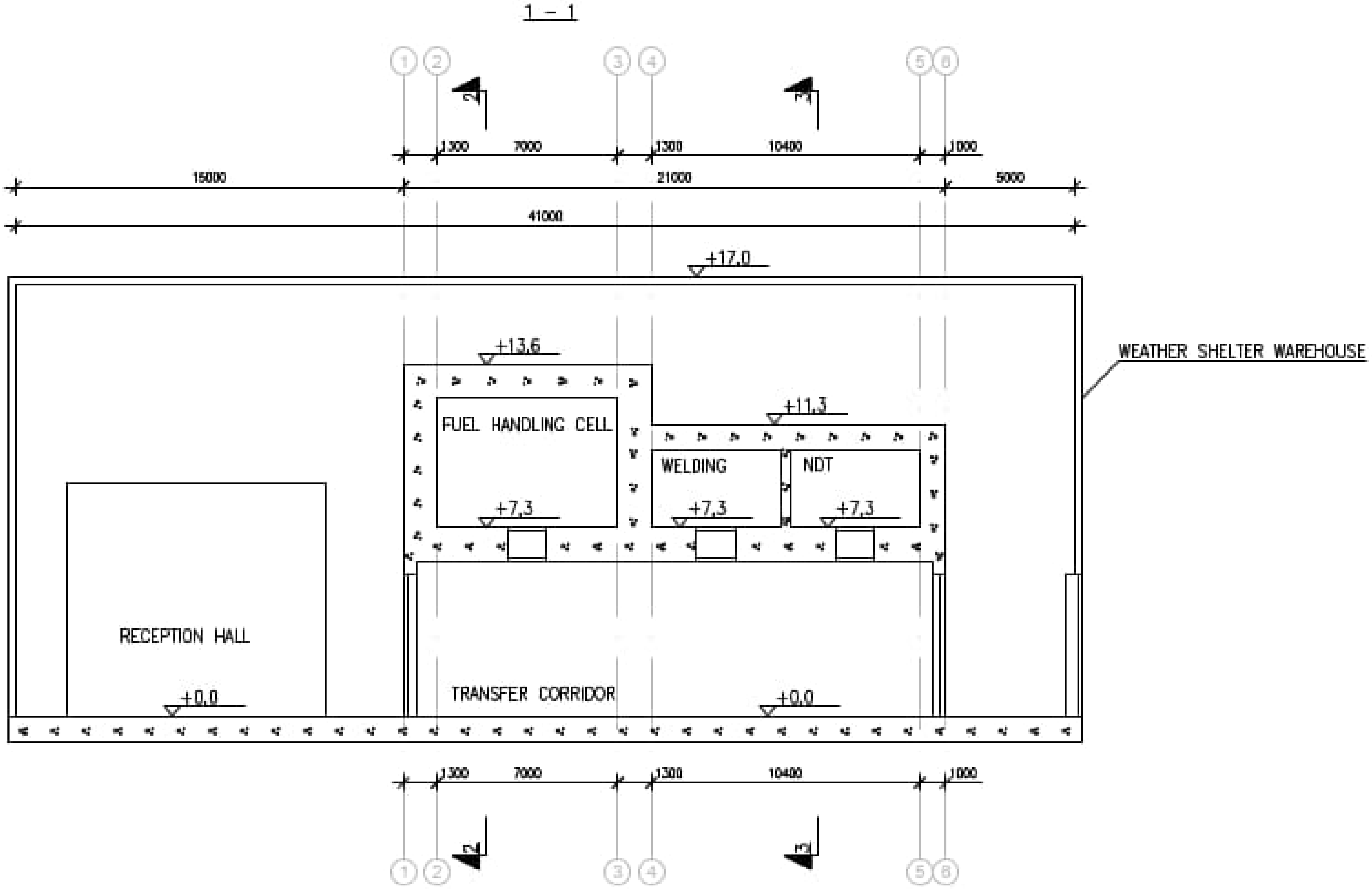

Figure 11-9 DBD section 1-1

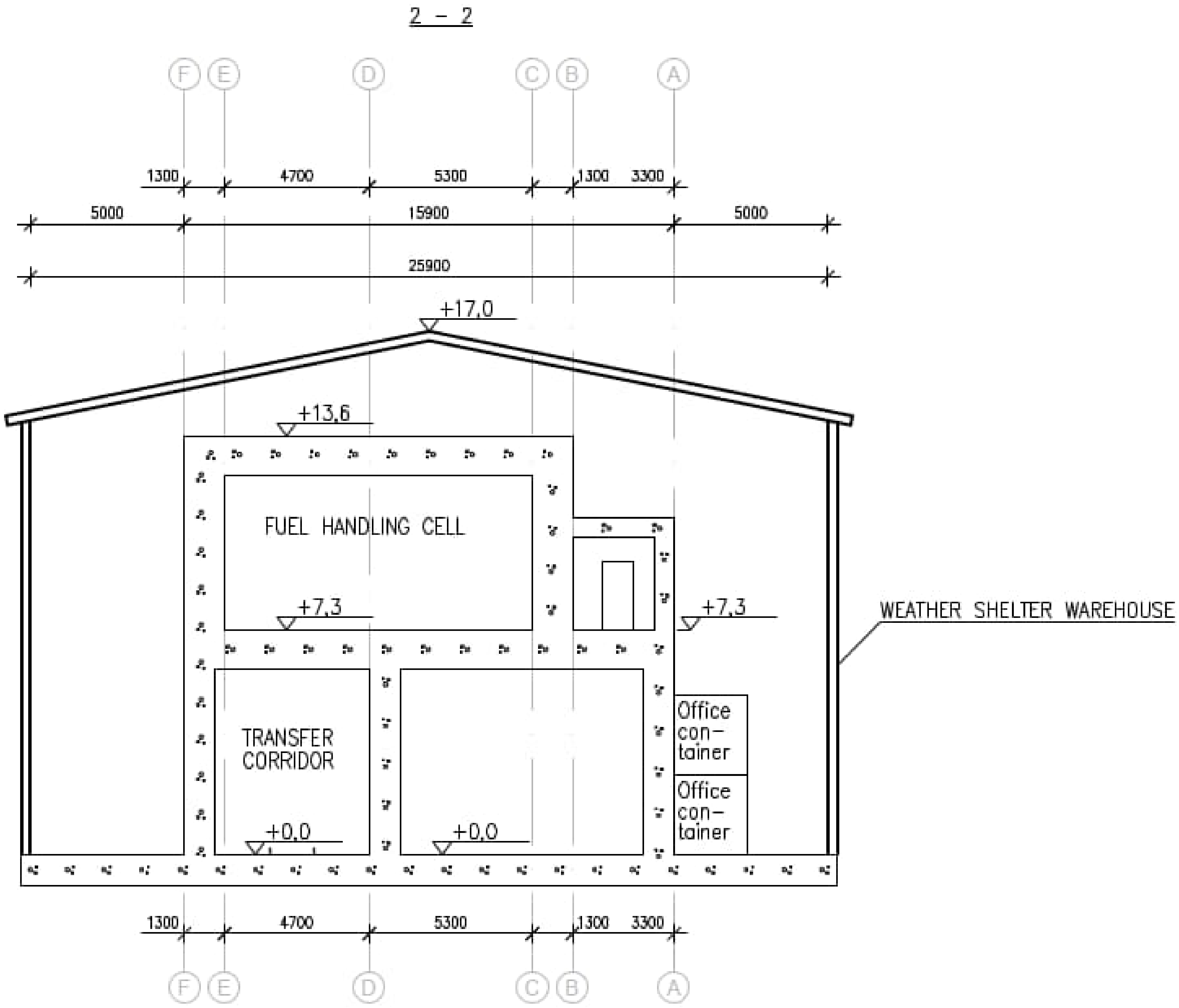

Figure 11-10 DBD section 2-2

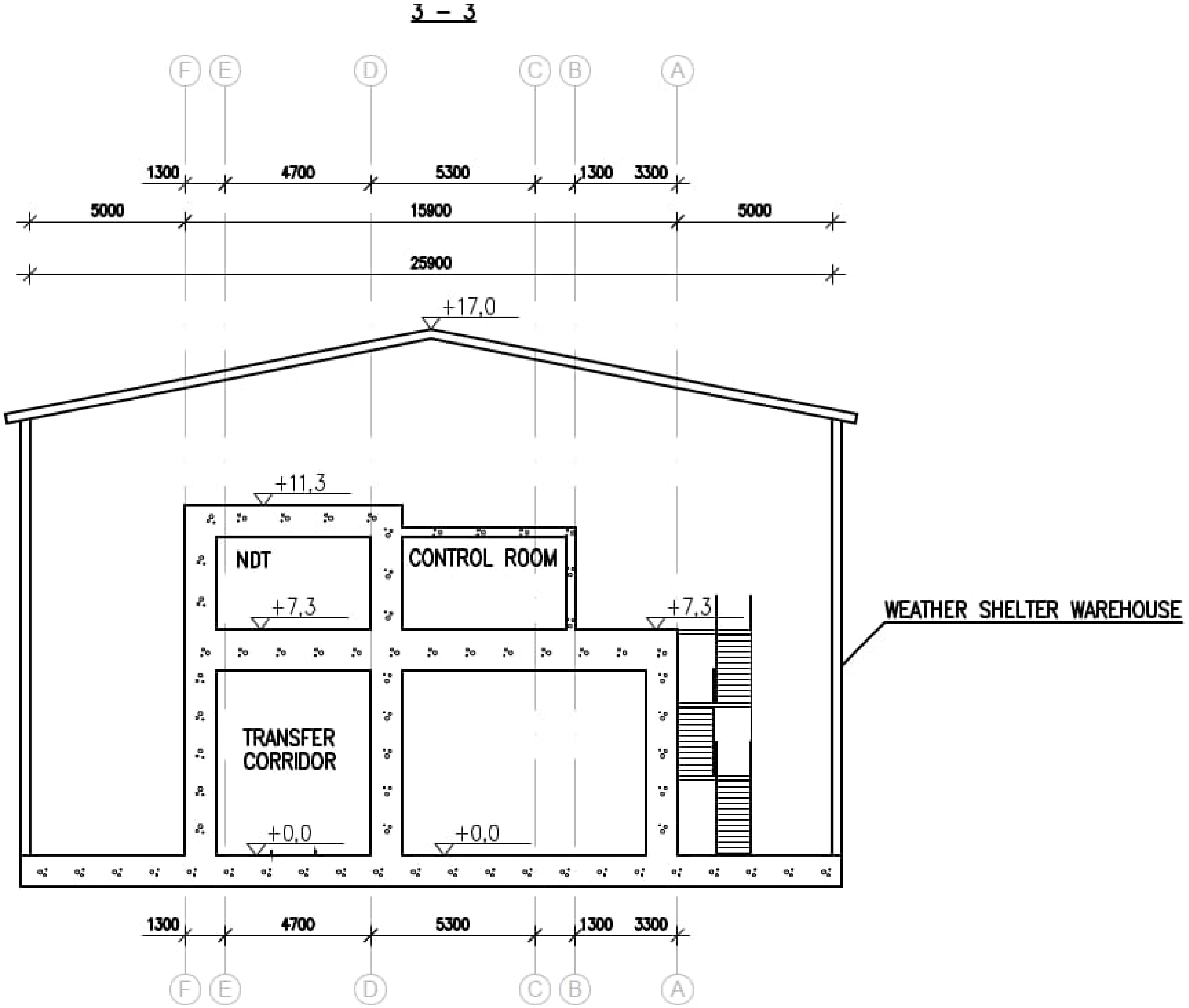

Figure 11-11 DBD section 3-3