NDE of the Spent Nuclear Fuel Disposal Canisters in Finland

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Abstract. The Finnish concept of high activity nuclear waste disposal is based on deep geological storage in copper canisters with cast iron inserts. The development of disposal concept and final disposal in Finland is managed and organised by Posiva Oy. Disposal canisters will be embedded in Olkiluoto bedrock at a depth of approximately 400 metres. Therefore it is essential to inspect the canisters with non-destructive testing (NDT) methods as well as possible before the final disposal.

The lid of the copper disposal canister for high activity nuclear waste is sealed with a weld. Before accepting the canister to the final disposal the weld is planned to be inspected by four non-destructive testing methods. These methods are ultrasonic testing (UT), radiographic testing (RT), eddy current testing (ET) and remote visual testing (VT) using cameras. The copper overpack and the lid are also inspected with multiple NDT methods; UT, ET and VT. The nodular cast iron insert is inspected with UT and VT.

In this paper the four NDT inspection methods (UT, RT, ET, VT) for inspection of different parts of the disposal canister are presented in brief. All information in this paper is collected and summarised from public reports and from the procedures of each method and inspection records. All of the four NDT methods detect defects in slightly different directions and based on different physical principles. The four methods are therefore supplements to each other in inspection of different parts of the disposal canister.

Introduction

The Finnish concept of nuclear waste disposal is based on deep geological storage in copper canisters with a cast iron insert. The development of disposal concept and final disposal in Finland is managed and organised by Posiva Oy. Canisters will be embedded in Olkiluoto bedrock at a depth of approximately 400 metres. Therefore it is essential to inspect the canisters with non-destructive inspection methods as well as possible before the final disposal.

The final disposal canister for high activity nuclear waste consists of a copper overpack, a copper lid and a nodular cast iron insert. The nodular cast iron insert gives strength to the structure of the canister to withstand the mechanical stress originating from the bedrock in the underground repository. Oxygen-free copper overpack forms a corrosion resistant shell to the canister. The copper lid of the canister will be sealed with friction stir welding (FSW) to the copper overpack.
During manufacturing defects may be generated in the components. The welding process may produce different types of welding defects, for instance voids, hooking, internal root defects, porosity and cavities [4]. Lifting of the canister at the encapsulation plant is one factor which could cause defects or make small existing defects grow. Thus, there is a limited number of lifts allowed. Possible handling incidents could cause defects on the outer surface of the copper overpack.

The disposal canister material quality as well as quality of the weld has to be verified according to acceptance criteria before the final disposal of the canister. Acceptance criteria for the canister are created to control and ensure the adequate strength and corrosion resistance levels for the canister. Non-destructive testing (NDT) methods give possibility to reveal defects in the base material and the weld. The four NDT methods used at the moment in the research are: ultrasonic testing (UT), radiographic testing (RT), eddy current testing (ET) and remote visual testing (VT) using cameras.

Several different inspection methods are used to gain the best possible information on different types of discontinuities. Ultrasonic and radiographic methods are used for volumetric inspections. Visual and eddy current methods are used for surface and near surface inspections.

Non-destructive testing of the canister weld is carried out in the encapsulation plant before the decision to move the canister to final disposal. The encapsulation plant (Figure 1) is located at the ground level above the actual repository. All NDT methods will be remotely controlled. Non-destructive testing in encapsulation plant is operated automatically in an isolated area because of the radiation from the high active spent nuclear fuel in disposal canister. The objective of the NDT testing is to acquire and analyse the data to detect possible manufacturing defects in the closure weld of the disposal canister.

Figure 1. The encapsulation plant is located above the actual repository (Posiva Oy).
The disposal canister consists of nodular cast iron insert, copper overpack and copper lid (Figure 2).

Figure 2. The disposal canister on the left. Different types of nodular cast iron inserts on the right for VVER 440, BWR and EPR (from left to right) (Posiva Oy).

**Nodular cast iron insert**

The main task for the nodular cast iron insert is to give adequate strength to the structure of the canister to withstand the mechanical stress originating from the bedrock in the underground repository. There are three different types of cast iron inserts (Figure 2), one for Loviisa 1 and Loviisa 2 (VVER 440 type), second one for Olkiluoto 1 and Olkiluoto 2 (BWR type) and third one for Olkiluoto 3 (EPR type).

**Oxygen-free copper overpack and lid**

Overpack including the bottom and the lid of the canister are made of oxygen-free copper which forms a corrosion resistant shell to the canister. Thickness of the overpack is 50 mm. In the first stage the geometry of the lid depended on the chosen welding method due to different weld orientation between electron beam welding and friction stir welding. In 2014 friction stir welding was chosen to be the welding method for the lid closure weld.

**Non-destructive evaluation**

At the moment three to four different methods are planned to be used for non-destructive evaluation of disposal canister. For surface and near surface inspections remote visual testing and eddy current testing are used. For volumetric inspections ultrasonic testing and possibly radiographic testing are used. In all inspections inspectors shall be qualified according to SFS-EN 473/SFS-EN ISO 9712 level 2 suitable for used method. Only in radiographic inspections the operator shall have at least a level 1 certification according SFS-EN 473/SFS-EN ISO 9712. Nevertheless the person evaluating the radiographic images shall have a level 2 certification according SFS-EN 473/SFS-EN ISO 9712.

**Visual testing**

Visual testing is conducted for all the disposal canister components including welds. The visual inspection in the encapsulation plant will be done remotely with cameras.
After the welding the surface of the upper part of the lid is to be inspected. Especially 100% of the weld area and the entire upper end of the lid are inspected. Also the vertical upper outer surface of the lid shell and the vertical inner surface of the lid are inspected. The illuminance degree is required to be high enough (minimum 500 lx). Additional lightning is needed from multiple lightning directions due to the variable reflection of the copper surface because of the characteristics of copper and its oxides. The surface to be examined is required to be clean.

The purpose of the visual testing is to verify, document and evaluate the surface area. During this inspection both manufacturing originated surface defects and handling defects can be detected. This information is critical for the integrity of the canister but also for verifying the indications primarily detected in eddy current testing and secondly by ultrasonic and radiographic testing. Especially outer surface defects which can be seen in radiographic images. Indications that exceed reporting limits will be reported by location, dimensions and defect type. Indication sizes correspondingly locations are tabled and compared to the relevant acceptance criteria. There are also stamped identification marks in the weld, lid and shell that need to be documented and checked.

**Eddy current testing**

Eddy current testing is a well-known and widely used surface inspection technique. In disposal canister inspection studies eddy current testing is a combination of low frequency and high frequency probe measurements. With high frequency technique surface breaking defects and surface extensions can be accurately measured. With low frequency eddy current technique deeper surface breaking defects and defects having small ligament can be evaluated. Overpack, lid and weld are inspected with eddy current technique. At moment the inspection is performed with specially designed equipment and analysis and visualisation software. The scan is visualised with in a form of colour coded C-scan (Figure 3).
A probe array consisting of pancake coils is held on the surface of the copper lid with a probe holder. The array and the holder are moved by a manipulator (Figure 4).

The lid is inspected using a coil probe array in order to detect defects. In inspection surface breaking defects will be detected, sized and classified. The inspection speed depends on the effective width of the probe array and on the frequency of the probe.

**Ultrasonic testing**

Ultrasonic testing is a volumetric testing method and in disposal canister inspections it is used for all the components of the canister. Phased array ultrasonic inspection is used for all inspections due to
possibility to modify electrically the sound field during the inspection. This enables the sound field adjustment dynamically for different situations and for detection of different types of flaws. In cast iron insert inspections also other ultrasonic methods are used. Frequency of phased array effects on detectability and sizing and therefore a good compromise 3.5 MHz for both is chosen for copper part inspections in the research phase of the process. At the moment ultrasonic inspections are performed using the Multi 2000 phased array ultrasonic system of M2M with 128 channels. During the examination of the FSW weld an ultrasonic transducer is scanning the top of the lid and the outer surface of the lid in circumferential direction. Simultaneously the phased array probe also carries out electronic scanning in axial direction. A-scan data in RF-form each measurement is stored. There are about 1500 measurement positions only in circumference.

As can be seen in Figure 5 the ultrasonic phase array probe is positioned on the outer horizontal surface of the canister at the distance of 0.1 mm from the scan surface.

An electronic scan is performed in the direction of the weld penetration. The longitudinal wave velocity in copper is \( v = 4760 \text{ m/s} \). The attenuation of the sound is dependent on the grain size in copper, bigger grains more attenuation. Large grains extending over 2 mm occur in the weld in circumferential direction. In radial direction the grain size is smaller but large enough to produce higher attenuation compared to base material of the tube and lid. In some cases also in the tube and the lid large variations in grain size can be detected. The grain size is controlled in the manufacturing process of the base material in order to minimise the grain size and its distribution. The ultrasonic testing will be carried out in local immersion at the encapsulation plant.

Before and after the examination the performance and the stability of the system is verified with a reference block containing different kind of reflectors. The block has the same geometry and material properties as the canister.

![Figure 5. Linear phased array ultrasonic testing of FSW weld.](image)

Nodular cast iron insert is also inspected with ultrasonic methods. The longitudinal wave velocity in nodular cast iron is \( v = 5600 \text{ m/s} \). Inspection is performed from the outer surface of the insert. First inspection is performed with 5 MHz phased array probe to verify the steel channel edge location and the channel distortion in casting (Figure 6).
Figure 6. On top nearest edge distance point in A-scan is the cross point of the back wall signal and noise where the signal rises up clearly from the noise. Below the minimum distance variation of each steel channel from the surface in axial direction measured from the top of the insert in millimetres.

After steel channel inspections 0° longitudinal wave curved 5 MHz phased array probe using different focus depths is used for certain areas of insert. Near surface area is inspected with TRL-70° longitudinal wave (conventional) probes using four inspection directions (0°, 90°, 180°, 270°). Technique TRL A means that the scanning occurs in axial direction and TRL C corresponding the scanning direction in circumferential direction. The fourth ultrasonic inspection for insert is performed using transmission technique with 2 MHz phased array probes to detect defects between the steel channels. At the same time with the same probes also transmit-receive inspection is performed for the same area. Due to three different types of inserts (BWR, VVER 440 and EPR) inspection is also highly dependent on the insert type.

Radiographic testing

Another used volumetric method is radiographic inspection. Radiographic inspection is used in research phase for the disposal canister welds and due to thickness of the component it is carried out at the moment with a 9 MeV linear accelerator. The centreline of accelerator beam is directed at 8° angle to the
weld [8]. For radiographic inspection a digital x-ray detector is used. As can be seen in Figure 7 the detector is placed behind the outer surface of the canister.

The high energy X-ray equipment used by SKB in Oskarshamn for pilot examination of the lid to canister weld consists of a 9 MeV linear accelerator (Varian Linatron 3000), a collimated line detector and a manipulator system.

![Figure 7. The radiographic setup with accelerator and the detector in SKB Oskarshamn site [8].](image)

The canister will be rotated in a carrier. Rotation speed is controlled by the RT-software that controls the radiation source and the detector. Before placing the canister on the carrier it is important to center it, the distance tolerance is maximum 1.5 mm. 100 % of the weld and the surrounding base material; is inspected. There is a marked zero-point on the canister surface. In the circumferential direction scanning exceeds the total circumference with suitable overlap. The 0 -point and the rotation direction are marked also to the examination plan.

Before the actual measurement of the canister, calibration test for intensity setting shall be carried out to check the proper intensity of the detector. A separate calibration block made of the same material as the canister with known wall thickness is used for calibration. The calibration of the measurement is carried out simultaneously with the weld inspection.

An image quality indicator (IQI) is placed on the detector side surface of the canister so that the calibration hole in IQI is visible on the x-ray image. Because the quality of the image cannot be controlled during scanning, the quality of the picture is monitored afterwards with IQI sensitivity and intensity value.

For examination the exposure voltage is nominal voltage of the 9 MeV x-ray accelerator. The minimum distance from source to object is defined as a factor of maximum allowed geometric unsharpness (Ug).

A minimum contrast ratio is defined for the display in order to evaluate data properly. The images are analysed partly already during the scan in the encapsulation plant.

Welding
Lid of the canister is welded with friction stir welding. Friction stir welding and electron beam welding methods have been studied and the final choice was made in 2014 by Posiva Oy.

**Friction stir welding**

Friction stir welding (FSW) is a solid state joining method originally developed by TWI. Basic principle is that the rotating tool is plunged between the pieces to be welded when the friction between the tool and the piece generates heat and plasticizes the welded material (Figure 8). Then the tool is moved to the wanted welding direction. There are many advantages in FSW. For example mechanical properties are good in as-welded state, automation is fairly easy and it can be operated in all welding positions [2].

In spite of advantages in FSW there are several possible defect types in FSW. These include [3,4]:

- pores and porosity
- worm hole
- voids
- oxide inclusions and entrapped oxide
- tool trace material
- incomplete penetration
- joint line hooking
- faying surface flaw

![Parameters to control](image)

Figure 8. Basic principle of FSW and parameters to control [5].

**Discussion and comparison to design criteria**

Cast iron insert is giving the main mechanical strength to entire disposal canister. Therefore it is essential to identify the criteria to be met. In the shear loading case a semi-elliptical flaw has been identified as the most dangerous flaw. Acceptable dimension of the flaw are 4.5 mm in depth and 27 mm in length [6,7]. As mentioned before for the insert surface area TRL ultrasonic inspection is used. In damage tolerance design $d_{95/95}$ is commonly used as a measure of the minimum size of the reliably detected flaw. With TRL ultrasonic inspection it is shown that in insert inspection this reliably detected flaw is 15.9 mm².
Compared to acceptable dimensions the reliably detected flaw could be almost six times larger. Therefore it can be concluded that this system is adequate for this inspection task. [6]

Above mentioned criteria is of course not the only criteria for the cast iron insert. There are many other criteria for example related to location of steel channels and geometry etc. which also partly applies to copper parts of the canister. These issues are not in the scope of this paper and are not presented in detail.

Copper overpack and the lid are the corrosion resistant and gas tight barrier of the disposal canister. One critical part of the copper canister is the weld. It is known that welding can cause different types of flaws in material as mentioned already earlier. FSW weld is inspected with all four NDT methods in the encapsulation plant. Studies made for SKB [7] have shown that for the copper part of the canister, no kind of postulated crack, defect or cavity of reasonable size has proven to be critical. The copper shell withstands the design loads with a good margin even with large postulated defects. The large variety of material testing that has been conducted during the studies has shown that the cracks in copper blunt under tension load and no crack growth is detected at applicable temperatures. With copper shell the main design criteria is the corrosion barrier and therefore all the found indications with different NDT methods are added together to verify the needed corrosion barrier thickness all over the disposal canister. In final disposal environment creep of the copper shell has been an issue of interest and there are several studies regarding creep behaviour of copper shell.

Conclusions

The disposal canister is designed to resist corrosion and to have adequate mechanical strength for final disposal environment. To be able to predict and ensure the integrity of the disposal canister certain design criteria has to be set. To ensure that the criteria are met non-destructive methods for inspections are needed. In this paper the four NDT inspection methods (UT, RT, ET, VT) for inspection of different parts of the disposal canister are presented in brief. All of the four NDT methods detect defects in slightly different directions and are based on different physical principles. The four methods are therefore supplements to each other in inspection of different parts of the disposal canister.

It is shown in different studies [6,7] that applicable criteria for cast iron insert is found and criteria can be verified with used NDT methods. For the copper parts of the canister as well as weld the most important criteria is the adequate corrosion barrier for the final disposal timeline. Studies have shown that the welds can be categorized according the quality and defects have been found [6]. Nevertheless there are still some techniques that need to be improved. At the moment there are lot of studies going on to improve the inspections in the area of non-destructive testing of disposal canisters. These studies include for example probability of detection, simulation, human factors, combination of inspection results etc..

References


