



Safe for 1 Million Years – NDT Matters!

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Abstract. The General Guidance in the Swedish regulations state that the safety assessment for a final repository for spent nuclear fuel should be 1 million years after closure. SKB developed the KBS-3 method, according to which the spent nuclear fuel is protected by three barriers. It is encapsulated in canisters with a diameter of 1 metre and a length of 5 metres. The canister consists of a cast iron insert surrounded by a 5 centimetre thick shell of copper. The canisters are disposed in the bedrock at a depth of about 500 meters surrounded by bentonite clay. In order to assess the safety over this extremely long period, an extensive quality control programme is applied to the canisters before deposit. In this programme, the use of non-destructive testing (NDT) is vital. The safety assessment of the canister in turn places high demands on the coverage, detectability, and reliability of the applied NDT inspections of the canister parts, i.e. cast iron insert, copper base, tube and lid, and the copper friction stir welds (FSW). This paper presents the extensive full-scale inspection development programme that runs at the Canister Laboratory in Oskarshamn (Sweden). In order to fulfil the high demands, phased array ultrasonic inspection techniques are developed using practical trials aided by ultrasonic modelling. The techniques apply, for example, different frequencies, inspection angles, focus depths, and both longitudinal and shear waves. Increased inspection reliability of the FSW is achieved by applying digital X-ray technique using a 9 MeV linear accelerator and a line detector. To complete the coverage, complementary surface inspections methods, i.e. eddy current array, magnetic flux sensor techniques and magnetic particle inspection, are applied. The canister safety assessment was the driving force to include reliability studies during the NDT development. Initially, the technical reliability was considered, resulting in development of advanced POD models (probability of detection). In combination with human factors studies, these models were implemented as tools in the development of the NDT techniques. Human factors studies were also applied to improve the inspection procedures to be more user-friendly enabling reliable inspections.

1. Introduction

The Swedish Nuclear Fuel and Waste Management Company (SKB) is responsible to take care of all radioactive waste produced in Sweden [1]. This includes primarily the waste produced by the nuclear power plants but also waste from the traditional industries, research and from the medical field, see figure 1. The spent nuclear fuel, which is the most critical portion of the waste, is stored for a minimum of 30 years in the central interim storage (Clab) in water basins 30 metres below ground. The operational waste is stored, surrounded by concrete, 50 metres below the ground in the final repository for operational



waste (SFR). These storages together and a ship, used for transportation of the spent nuclear fuel, are running since about 30 years. What still needs to be built is an encapsulation plant where the fuel will be encapsulated and a final repository for the spent nuclear fuel. In 2011 SKB submitted an application to the authorities to build the encapsulation plant in connection with Clab in Oskarshamn and the final repository in Forsmark. After approval from the authorities, the construction work will start around 2020 and, after about 10 years of constructions, the deposition of canisters will start.

For the final disposal of the spent nuclear fuel, SKB is developing a method, called the KBS-3 method. The method is based on three protective barriers, see figure 2. The first barrier is the canister composed of a nodular cast iron insert surrounded by a copper shell. The impermeable copper canisters are then embedded in bentonite clay that serves as the second barrier and finally placed in the crystalline basement rock (third barrier) at a depth of about 500 metres, which serves as the third barrier. Finally, after the canisters have been disposed, the tunnels and rock caverns will be sealed.

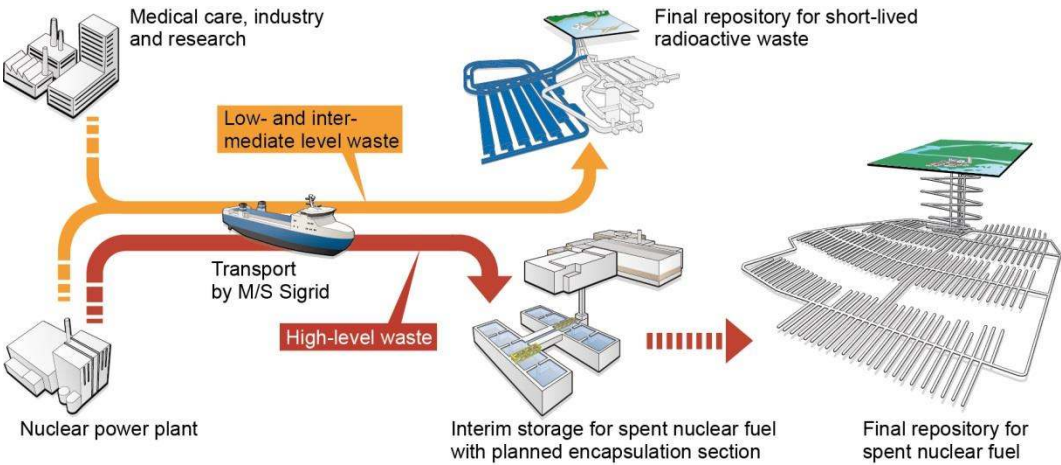


Fig. 1. SKB’s system for managing the radioactive waste in Sweden.

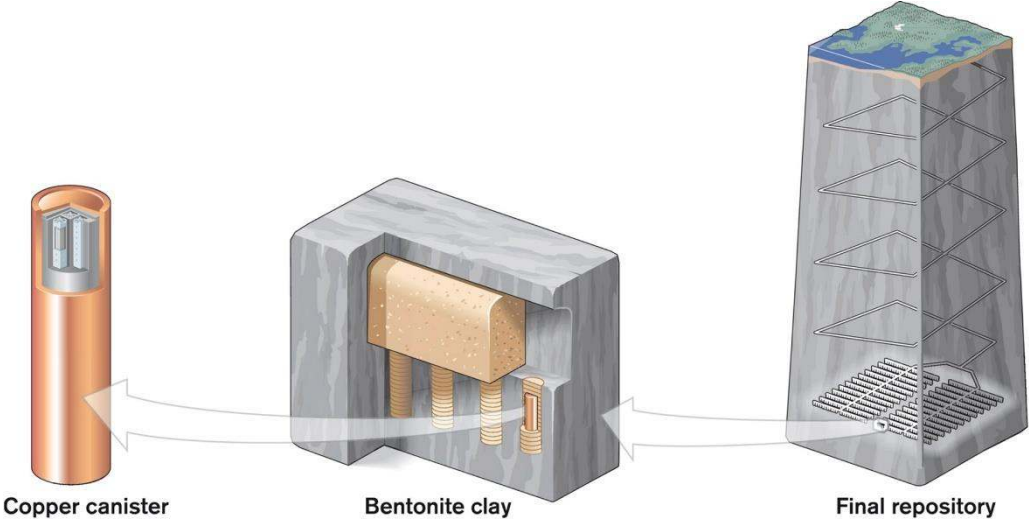


Fig. 2. The KBS-3 method with the different barriers.

2. Long-term Safety

In the Swedish regulations [2] it is indicated that the time scale of a safety assessment for a final repository for spent nuclear fuel should be one million years after closure. A detailed

risk analysis is required for the first thousand years after closure. Also, for the period up to approximately one hundred thousand years, the reporting is required to be based on a quantitative risk analysis. For the period beyond one hundred thousand years, the General Guidance states that a strict quantitative comparison of calculated risk in relation to the criterion for individual risk in the regulations is not meaningful. Rather, it should be demonstrated that releases from both engineered and geological barriers are limited and delayed as far as reasonably possible using calculated risk as one of several indicators.

After approximately one hundred thousand years, the radiotoxicity of the spent nuclear fuel is comparable with that of the natural uranium ore once used to produce the fuel [3]. Furthermore, the sum of toxicity of all fractions originating from the nuclear fuel cycle (the daughter nuclides separated from the uranium prior to enrichment, the depleted uranium arising in the enrichment process and the spent fuel) is comparable to that of the utilised uranium ore after one hundred thousand years, see figure 3.

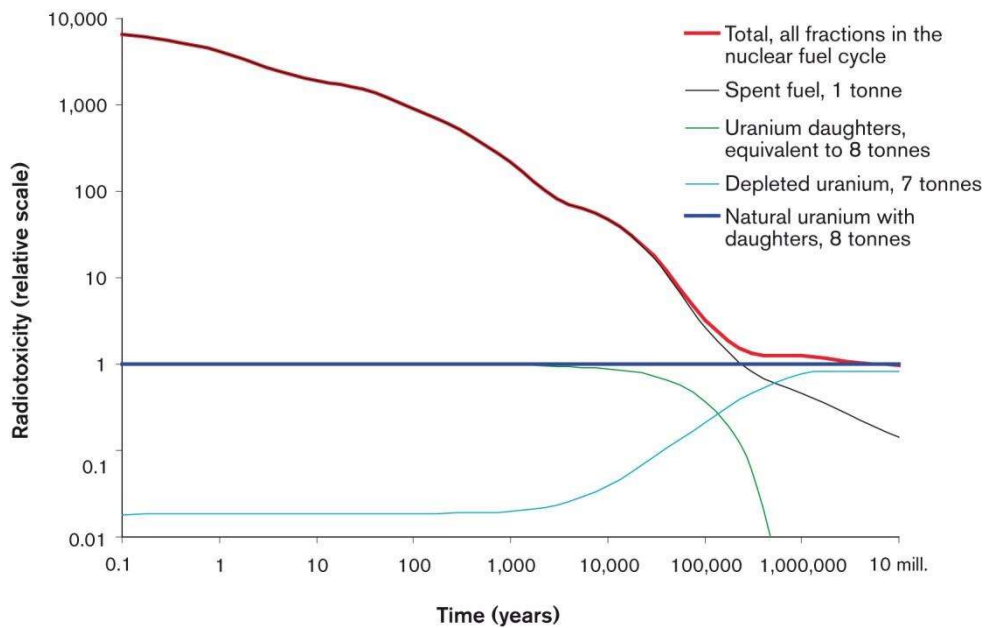


Fig. 3. Radiotoxicity over time for the Swedish spent nuclear fuel.

3. The Canister

The copper canisters designed for encapsulating the spent nuclear fuel are nearly five metres long and over one metre in diameter [1]. The weight is between 25 and 27 tonnes including about 2 tons of spent nuclear fuel. The canister, see figure 4, is composed of a nodular cast iron insert surrounded by a 5 cm thick copper shell. The insert is manufactured in two different types: the PWR (pressure water reactor) type with four steel channels and the BWR (boiling water reactor) type with twelve steel channels. The main functions of the insert are to contain the fuel and withstand the mechanical loads in the repository. The copper shell, which serves as the corrosion barrier, consists of a lid and a base that are welded to the tube by friction stir welding (FSW).

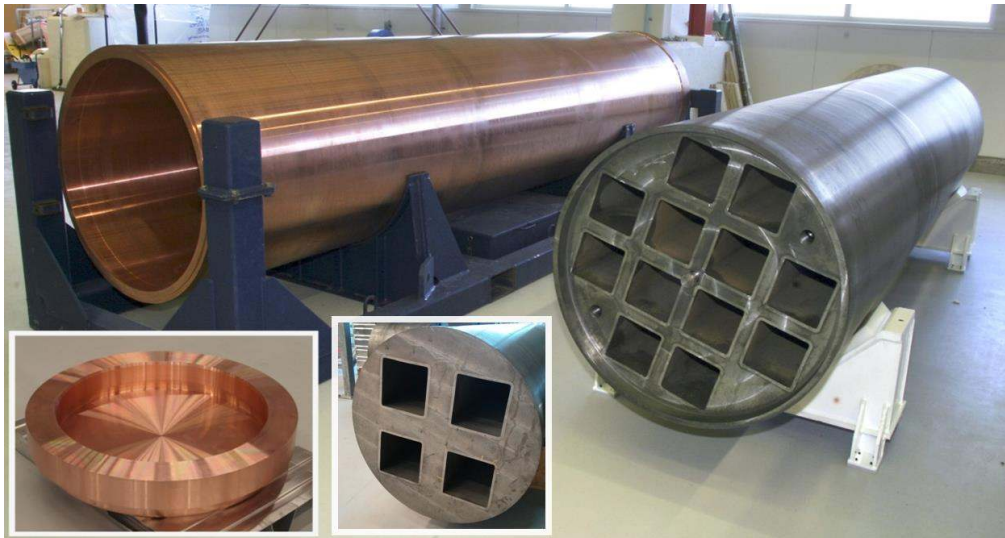


Fig. 4. The canister components.

4. Non-destructive Testing of the Canister Components and Welds

The general strategy to achieve the high safety assessment is to develop manufacturing and welding processes, which by margin can produce canisters that fulfil the requirements with respect to mechanical strength of the cast iron insert and the copper shell thickness. However, due to the extreme long-term safety assessment, the non-destructive testing (NDT) needs with a high confidence verify that the requirements are fulfilled and this set high demands on the coverage, detectability, and reliability of the applied NDT.

Commonly, when a new product is developed, the application of NDT is considered late in the development process. The design of the canister using thick-walled welded copper is rather unique. Therefore, SKB identified the need for a facility for full-scale welding trials and in order verify the weld process development the need for NDT resources was high-lighted.

4.1 The Canister Laboratory

The Canister Laboratory in Oskarshamn, see figure 5, was built in 1998 to develop and test techniques for full size welding of the copper lid to the copper tube, non-destructive testing of the weld, and handling of canisters in a similar way as for the planned encapsulation plant. Over the years the activities at the laboratory have been expanded to become a centre for encapsulation techniques for the canister. This means that the work also includes detailed construction and verifying calculations of the canister as well as development of manufacturing processes (together with external suppliers) and NDT techniques for the canister components.

The Canister Laboratory is equipped with full-scale inspection systems for the canister components and welds. This includes systems for digital X-ray inspection of friction stir welds as well as phased array ultrasonic and eddy current array inspection of friction stir welds and canister components (i.e. copper tubes, lids and bases and cast iron inserts). To increase the reliability of the inspection of the large components (copper tube and cast iron insert), reference blocks with real component geometry are integrated in the inspection system, see figure 6.



Fig. 5. The Canister Laboratory.



Fig. 6. Manipulator for the cast iron insert with the reference block to the left.

4.2 The Development Process

The canister components cannot be seen as conventional products, especially when considering the construction material (thick-walled copper) and the large volume and complex geometry (cast iron insert) in relation to the very high demands. Therefore, the interaction between the development of the manufacturing and welding processes and the NDT has been found to be crucial. This interaction was first initiated for the weld process where the knowledge of possible defects in friction stir welding of thick copper was limited. In this case, the relation between welding parameters and creation of defects was seen to be of special interest. This has then formed a basis for the iterative development process applied for the NDT of the whole canister, see figure 7. The special safety assessment for the canister and the applied inspection techniques, as well as the fact that the development programme runs over about two decades, make more room for more iterations than normally in NDT development. The process can be described in the following steps:

- Definition of NDT technique – For the first iteration an estimation of the best suitable technique is identified and by the use of existing equipment and probes, a preliminary inspection technique is defined. For upcoming iterations the gained knowledge during the previous iterations and from development of similar techniques are used to define the inspection technique.
- NDT Development – The practical development of the NDT technique involves a number of activities depending on the complexity. For example, modelling is used both to design ultrasonic phased array probes and define the ultrasonic setup to be tested. To verify the modelling and tune the inspection sensitivity, reference objects with “true” component geometry is constructed. To make sure that the full-scale inspections are performed reliably, rigid probe fixtures are constructed and also great emphasis is put

on creating good NDT instructions. By applying both theoretical and practical studies as well as incorporating the users in the final implementation, detailed and user-friendly NDT instructions have been created [4].

- Full-scale inspections – To test the techniques and the instructions, full-scale inspections and evaluation of the collected data are performed, under supervision, by an inspector not directly involved in the development.
- Evaluation – Evaluation of NDT techniques is the most diverse iteration step. First of all, the practical application of the technique is evaluated, e.g. do the probes, the fixtures and the scanning sequences work as intended? Secondly, the real performance of the technique is evaluated. This is done both from a general sensitivity point of view by, for example, applying POD-models (probability of detection) based on signals from artificial defects and by analysing the sensitivity for real defects. To consider several parameters, like for example, ultrasonic attenuation and defect depth, special multi-parameter POD-model has been developed [5]. The analyses of real defects are, based on the characteristics of the defects, done by either a combination or individual examinations, like for example additional NDT inspections, computed tomography and metallographic examinations of areas of interest. In addition, for some chosen techniques or combination of techniques the practical use of the NDT in relation human factors is analysed. This has been done in different workshops in which Failure Modes and Effects Analyses (FMEA), customised to the applied mechanised inspection, have been used [6].
- Gap analysis – In the gap analysis, the performance of the individual and combination of NDT techniques are compared to the present acceptance criteria (the final acceptance criteria are not yet fixed) and the gaps of importance is highlighted.
- Definition of further actions – Based on the results of the gap analysis, different grades of further actions are defined. For example, minor gaps could require optimisation of the technique while the more severe gaps require that additional techniques need to be developed and even that more precise acceptance criteria needs to be defined.

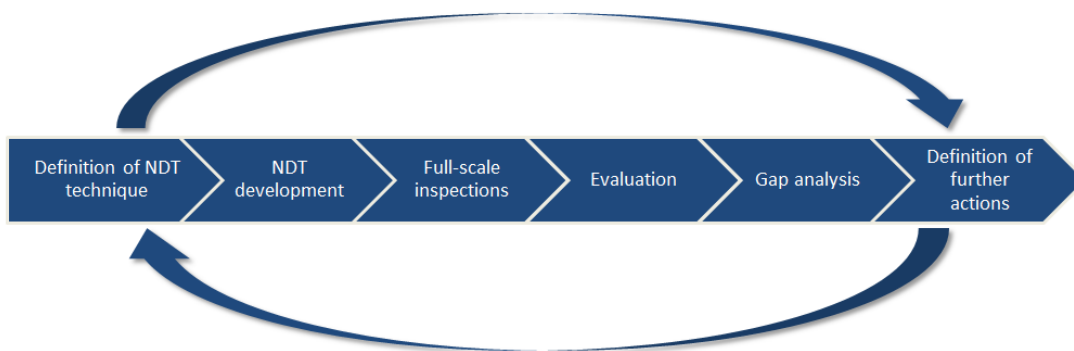


Fig. 7. The NDT development process.

In addition to the work described in the development process above, the interaction between the development of NDT techniques with the development of the manufacturing and welding processes is important. For example, results from full-scale inspections are used to get a more clear understanding of the component material and defect characteristics, which in turn can be used to further develop more reliable manufacturing and welding processes. On the other hand, good knowledge of the manufacturing and welding processes can be used to create defects necessary to develop and verify the reliability of the NDT.

4.3 Applied NDT Techniques

In this section the techniques currently used and evaluated at the Canister Laboratory are briefly described.

4.3.1 Inspection of the Cast Iron Insert

The inspection of the nodular cast iron insert is a very complex task because of the large volume, the complex geometry and the fact that the shape of the possible casting defects normally not is well defined. In addition, the NDT requirements still have not been set, giving goals that vary during the development. Based on this, several complementary techniques are being developed and evaluated. For the main volume different types of ultrasonic techniques primarily are applied, see figure 8 and 9. In order to get as large coverage as possible, the near-surface limitations are being overcome by performing the inspection in a state before the insert is machined to its final dimensions. After final machining, dedicated surface inspections are applied.

The primary ultrasonic technique applies local immersion 0° ultrasound (3.5 MHz) using linear phased array technology to achieve a good and homogeneous sound field down to the 200 mm depth. To get complementary inspection directions (60° - 70°) for this volume, two additional techniques using different designs of linear 1.7 MHz shear wave array probes are applied. The central volume of the insert is inspected by two linear 2 MHz array probes working both in pulse-echo and in transmission.



Fig. 8. The different phased array ultrasonic inspection techniques for the insert. Normal incidence local immersion (left), angular shear wave (middle) and transmission (right).



Fig. 9. The different phased array ultrasonic inspection techniques and their associated setups for the insert. Normal incidence local immersion technique (left), two versions of angular shear wave (middle) and transmission techniques (right).

Based on the fact that some limitations have been identified in the ultrasonic inspection of the central volume, a study has been conducted to identify the possibility to X-ray this volume. The study included both practical experiments and simulation on BWR and PWR insert segments, see figure 10. For the inspection of the surface, magnetic particle inspection is the common method used for these types of large castings and this technique is also applied for inspection of the insert surface. However, due to the fact that this manual

technique is rather arduous for the operator, dependent on the operator skills and awareness as well as the fact that the technique might cause not acceptable contamination of the surface, other techniques are being considered. For example, eddy current techniques using both conventional and array probes as well as the use of magnetic flux sensor techniques have been tested.

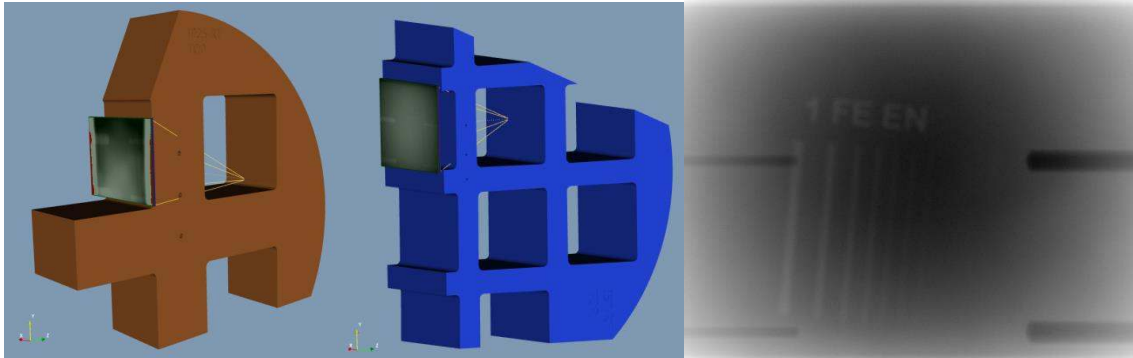


Fig. 10. Simulation of X-ray of the central volume of the insert: PWR insert setup (left), BWR insert setup (middle) and simulation results of BWR insert inspection (right).

4.3.2 Inspection of copper components

The inspection of the copper components, i.e. the tube, lid and base, can, in the same way as for the insert, be divided into volumetric and surface inspections. The volumetric inspections are, as for the insert, conducted using a 3.5 MHz 0° linear array, see figure 11, which for the tube is applied by local immersion technique while the lid and base, that in the stage for the ultrasonic inspection have the same geometry, are inspected immersed in water. The lid and base geometry, at the stage for the volumetric inspection, have been designed to facilitate the ultrasonic inspection with as high sensitivity and coverage as possible, while the tube in the same way as the insert has some additional material to overcome the ultrasonic limitations close to the surface. After final machining of the copper components, eddy current techniques using both conventional and array probes are evaluated for the final surface inspection.



Fig. 11. Local immersion ultrasonic inspection of the copper tube (left) and ultrasonic immersion inspection of the copper lid/base (right).

4.3.3 Inspection of friction stir welds

The inspection of the copper friction stir copper welds will, due to the fact that the weld will seal the canister and thereby being the final step in the encapsulation process, requires very high confidence. Therefore, it has been judged that several complementary methods

should be applied, see figure 12. First, the weld is inspected by digital X-ray technique using a 9 MeV linear accelerator as an extreme X-ray source and a linear detector array for collection of the data. Secondly, phased array ultrasonic inspection using a 3.5 MHz linear array is used by applying several inspection angles and focus depths. Finally, the weld surface is inspected by eddy current array technique.



Fig. 12. Inspection of the copper friction stir weld: Digital X-rays (left), phased array ultrasonics (middle) and eddy current array (right)

5. Conclusions

The very special safety assessment that the canister has to remain tight for up to one million years set very special requirements on the manufacturing and inspection processes applied for the canister. The systematic iterative development of NDT techniques has been used not only for development of the NDT techniques, but also as input to develop reliable manufacturing and welding processes. Several different NDT techniques have so far, using diverse options of tools, been developed and tested in full-scale. The techniques have been evaluated from technical basis using both empirical and statistical models and in addition also from the human factors point of view.

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