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Advanced nondestructive methods for inspection of canisters for spent nuclear fuel

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Sweden has been intensively developing methods for long-term storage of spent fuel from nuclear power plants for twenty-five years. A dedicated research program has been initiated and managed by the Swedish company SKB (Swedish Nuclear Fuels and Waste Management Co.) in collaboration with many research groups in different countries. After the interim storage, SKB plan to encapsulate the spent nuclear fuel in copper canisters with inserts made of cast iron. The canisters will then be placed in a deep repository located at a depth of 500 m in the bedrock. The canisters, when filled with fuel rods will be sealed using electron beam technology. This paper discusses NDE techniques used for assessing the weld in copper canisters. Three complementary NDE techniques are briefly presented, radiography, ultrasound, and eddy current. Presently, all the NDE techniques are verified in SKB's Canister Laboratory where full-scale canisters are welded and examined.

1. KBS-3 method for long term storage of nuclear waste

One of the most important arguments against nuclear power plants is the issue of nuclear waste that has to be disposed in a very long time before it becomes harmless for living organisms. Especially sensitive is the problem of spent nuclear fuel that can be no longer used in the reactors but still emits strong radiation and is characterized by a very long half-time.

Sweden is one of a few countries where this problem has been considered already during the construction of the nuclear power plants and a special research project aimed at developing save method for long term storage of nuclear waste has been initiated. The Swedish Nuclear Fuel and Waste Management Co. (SKB) have been responsible for this project. As a result, SKB in collaboration with many research organizations round the world have developed the technology KBS-3 for long-term storage of spent nuclear fuel. The fuel rods taken from the reactor will be encapsulated and placed in a special deep repository situated at the depth of approx. 500 m in the bedrock, cf. [1].

The radioactive material will be protected against the environmental factors by a triple barrier consisting of copper-lined canisters embraced in clay-lined holes and located in crystalline bedrock (see Fig. 1a). The canisters will have the form of 5 m high copper cylinders with diameter 1 m, and a copper wall thickness 50 mm (see Fig. 1b). The fuel rods will be placed inside the canister in a cast iron insert that separates the rods and yields the mechanical strength.

The most dangerous threads for the canister down in the repository are corrosion and the risk that it will be broken due to the movements of the rock. The main function of the copper lining is sealing the canister to isolate the fuel from the ground water present in the rock. Performed analysis has shown that copper well resists aggressive corrosion mechanisms present in the ground water.

When canister is filled with fuel rods a copper lid is welded on its top in a special vacuum chamber using a high power electron beam (EB) that melts the copper and joints the lid with the walls (cf. Fig. 1c). The EB weld joins both canister parts by solidification across the weld interface. The reduced pressure electron beam welding process used here produces narrow, deep penetrating weld zones with rounded roots that substantially reduce the occurrence of weld root defects. This process results in a cast microstructure, which can contain porosity and other associated weld flaws. The porosity occurs mainly due to the fact that melted copper floats out from the weld zone. The EB weld due to its cast structure and possible presence of porosity is considered as a weak point that has to be inspected very carefully.

It is worth noting that the weld is not supposed to withstand any considerable mechanical loads but it has to be absolutely tight. The most dangerous flaws would take the form of porosity located near the outer canister surface. If oxygen and water, despite the bentonite clay barrier enter the void a corrosion process may start. Taking into account a very long storage time (100 000 years) this process could, in the worst-case lead to substantial loss in copper lining and leakage of the radioactive material to the ground water.

To reduce that risk the weld will be thoroughly assessed by means of non-destructive methods. Three different NDT methods will be used in parallel: X-ray radiography, ultrasound, and eddy current. Since the above-mentioned methods have different features they will complement each other to achieve very high inspection reliability. Radiography and ultrasounds will be used for the inspection of the whole weld volume while the eddy current inspection is aimed at the detection of surface breaking and subsurface flaws.

The above requirements concerning canister tightness resulted in the specification concerning sensitivity of the NDT methods used for the weld inspection. A schematic of canister wall and lid is presented in the Fig. 2 together

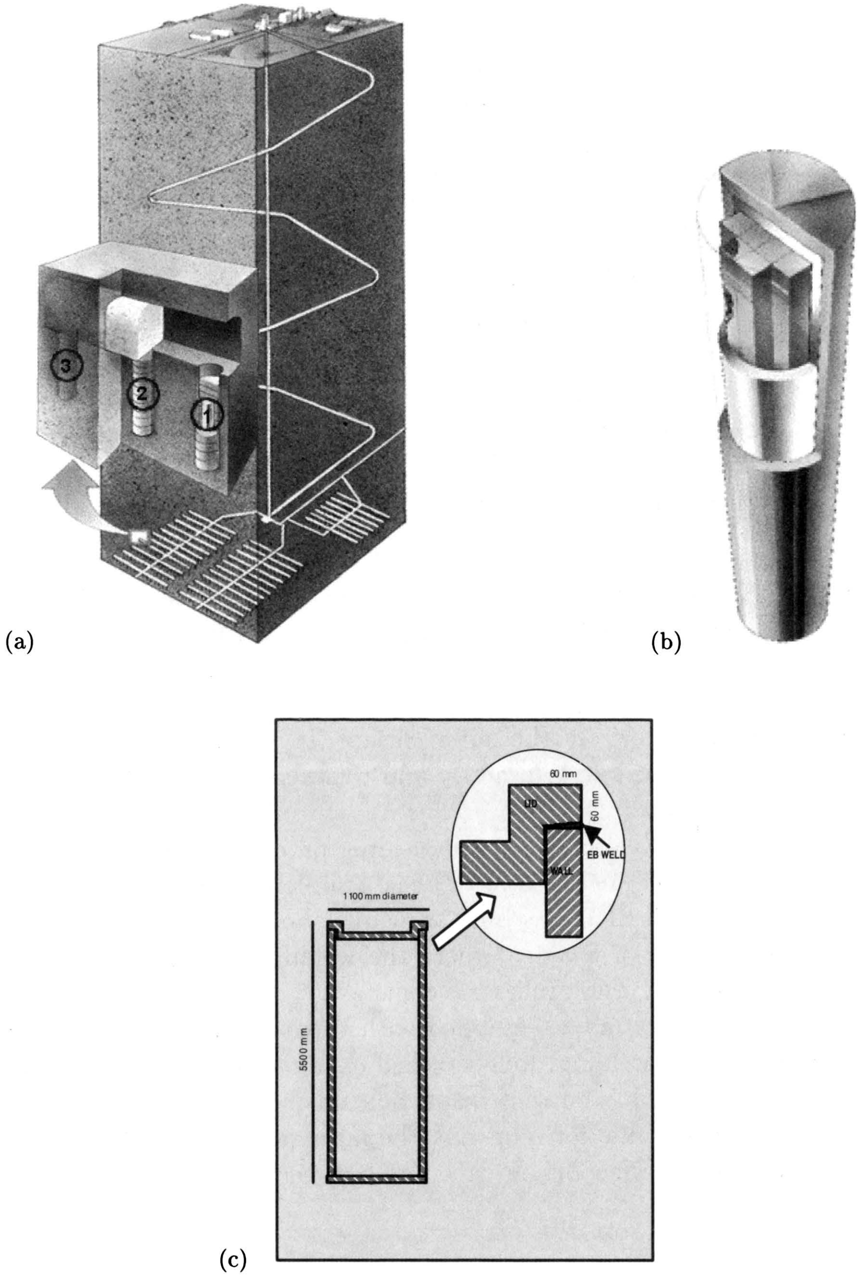


FIGURE 1. Technology KBS-3 for long-term storage of spent nuclear fuel. (a) Deposition tunnels in the repository and the triple barrier. (b) Schematic illustration of canister for spent fuel. (c) Cross section of the canister and the detail showing weld between the canister lid and wall.

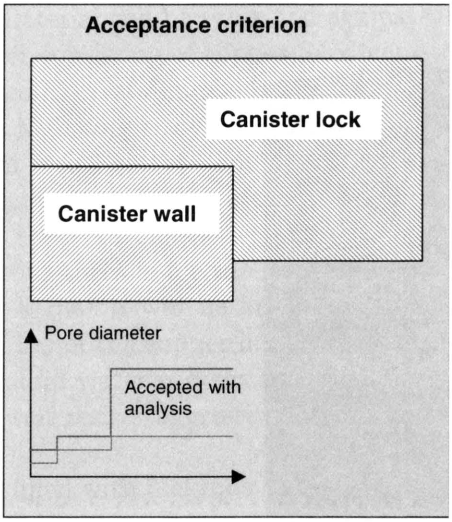


FIGURE 2. Required sensitivity of the NDT as a function of defect depth.

with the acceptance curve [4]. This curve indicates the size of defects that have to be detected as a function of depth counted from the outside canister surface. It is clear that the highest sensitivity is required just below the outer surface (up to 2 mm) and the sensitivity is reduced in steps with the increasing distance from the outer surface. It is obvious that this stepwise curve is non-realizable in practice and therefore it should be treated as recommendation only.

Recently, basic development of EB welding process as well as laboratory evaluation of the NDT methods have been completed and the second stage of the project started. SKB has built canister laboratory in Oskarshamn in the southeastern part of Sweden where the welding process and the NDT methods can be tested using full-scale canisters.

The canister laboratory is equipped with three separate test units: vacuum chamber for EB welding, well-screened chamber for radiography, and a combined ultrasonic eddy current inspection unit. The latter unit contains also large milling machine for removing the material overflow after welding. A special system for transporting canisters between the units has also been constructed.

2. Canister assessment using NDT

Three complementary NDT techniques have been developed to ensure that the criterion presented in Fig. 2 is fulfilled as close as possible:

- X-ray radiography providing a high resolution in the whole weld volume,
- ultrasonic inspection using phased array, for reliable defect localization,
- eddy current inspection detecting small subsurface defects close to the canister outer surface.

Combination of the above listed methods should guarantee very high inspection reliability and create means for reliable defect sizing.

3. Radiography

The radiographic inspection requires a strong source, capable of penetrating thick copper section at an angle of approx. 30° to the weld plane, see Fig. 3. A linear 9 MeV accelerator from Varian generates strong beam penetrating approx. 150 mm copper and entering a collimator and a digital detector. The detector is connected to a PC that enables presentation and storage of the result and defect localization. Accurate localization of defects can be difficult due to the low incidence angle at the weld plane.

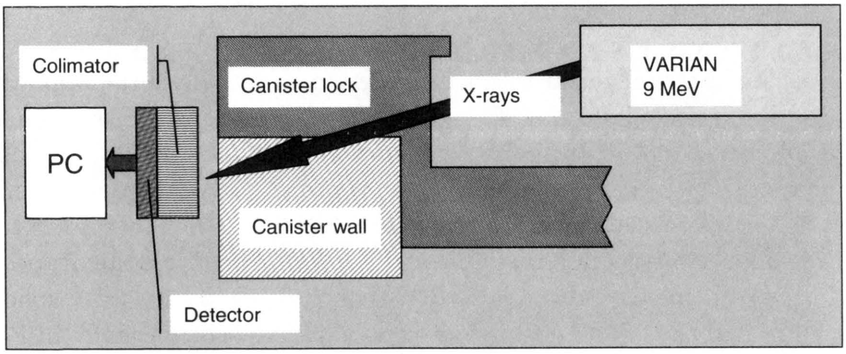


FIGURE 3. Setup of the X-ray canister inspection using linear accelerator and digital detector.

The computer has a software tool for compensating effects of variable ray paths in copper for different rays in the beam. An additional difficulty arises due to the irregular outer weld surface (radiographic inspection of the canister is conducted before machining the canister).

Since radiographic inspection carried out using high energy X-rays requires proper safety precautions, the equipment is installed in a special chamber surrounded with thick concrete walls damping scattered radiation. The canister is placed in the chamber through a hole in the floor (see Fig. 4).

FIGURE 4. Inside view of the radio-graphic chamber. Canister is lifted up through a hole in the floor. The ray source is seen in the second plan.

4. Ultrasonic inspection

Novelty in the canister ultrasonic inspection technique is the application of phased array technique [2-4]. There are several reasons for this solution, first of all, flexibility in beam-forming and elimination of one mechanical movement during the inspection. The array is placed above the upper canister surface at a fixed position while the canister is slowly rotated on its turntable. The mechanical construction is simple and reliable. The ultrasonic inspection is performed in pulse-echo mode and C-scan images of the weld zone are produced in real time. The inspection setup is shown schematically in Fig. 5.

An ultrasonic array made of composite material is placed above the top surface of the canister lid. Multi-channel electronics is capable of beam-steering, in particular, focusing, steering and scanning.

During focusing the beam is concentrated in the weld zone (approx. 60 mm under the surface). Steering enables inclining the beam close to the outer wall. Scanning that moves the beam along the canister radius eliminates mechanical movement and increases inspection speed. Beam-steering is performed electronically both in the emission and reception by introducing phase difference (delays) between the individual array elements. This operation is relatively simple in transmission but it requires delay elements for the received signals in the reception. Delay in reception is performed using analog delay lines but in modern array systems signals received by the ar-

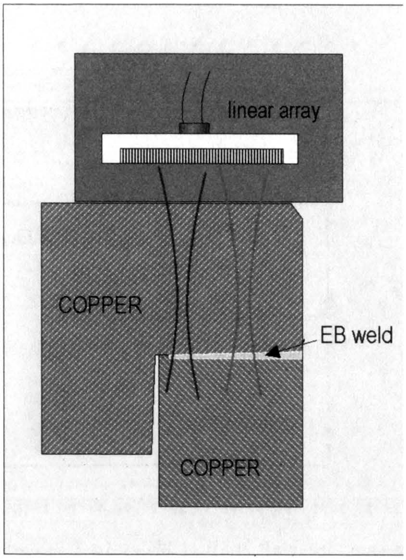


FIGURE 5. Ultrasonic inspection using phased array.

ray elements are first digitalized and then delayed. The delays are chosen properly to obtain desired beam pattern.

Only a group of array elements (aperture consisting of 16 to 32 elements) is used for the emission and reception of the beam. This aperture can be moved along the array by switching (multiplexing) the respective elements to obtain electronic scanning.

It is clear that the ultrasonic phased array technique applied for canister inspection enables changing the beam pattern without performing any physical changes in the transducer, which ensures high inspection flexibility. It is worth mentioning that electronic scanning can be performed at much higher speed than that available for mechanical scanners. Due to this feature inspection of a complete weld could be reduced from several hours to less than 20 minutes.

To illustrate ultrasonic imaging we present an example of the inspection of a test specimen with artificial defects (drilled holes), see [3, 4]. The specimen, shown in Fig. 6 has the form of a small section of canister and lid welded together with EB weld in the middle. The specimen was inspected in immersion using a 64-element array with center frequency 3 MHz and element width 1 mm. A 16-element aperture used for this inspection resulted in B-scans consisting of 49 lines (A-scans). En example of B-scans obtained using electronic scanning of the specimen using respectively unfocused and focused aperture is shown in Fig. 7.

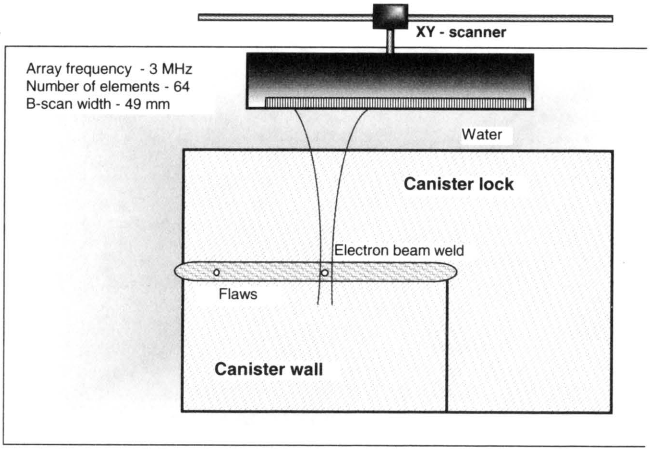


FIGURE 6. Canister section with drilled holes in EB weld used in experiments.

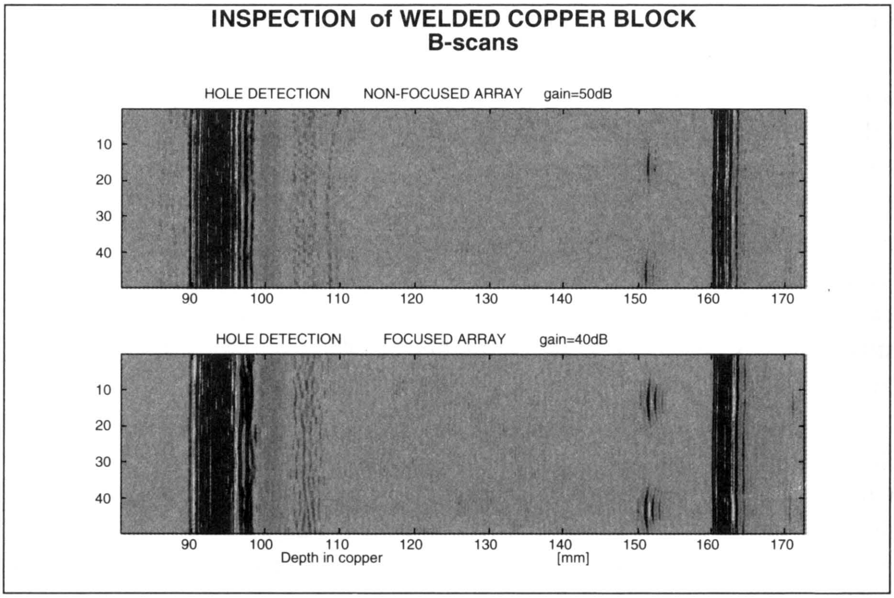


FIGURE 7. B-scans showing echoes from the side driled holes in EB weld in the specimen from Fig. 6. The upper image was obtained for unfocused 16 element aperture while the lower for the focused one.

In the B-scans aperture position is shown on vertical axis while the horizontal axis is proportional to the depth in copper (time). Two strong echoes from the top and bottom surfaces of the specimen are located at the left and right side of the B-scans, respectively.

Two characteristic hyperbolic echoes from side drilled holes with diameters 2 mm and 2.5 mm are well pronounced at the depth 60 mm in copper (150 mm in the figure). It is clear that at least 10 dB in amplification can be gained due to the focusing. Improvement in lateral resolution is difficult to evaluate from Fig. 7 but other experiments and modeling have shown that the lateral resolution can also be considerably improved due to focusing.

Since the weld area is very large and defect detection using B-scan images would be very laborious, the inspection result is presented in the form of C-scan. The C-scan image showing echoes scattered in a certain depth interval can be regarded as material cross section in horizontal plane. Both echoes' amplitudes and scatterers' locations can be evaluated from the C-scan image. If more thorough analysis is required all individual echoes (A-scans) are stored in the computer memory.

In the case of EB weld an ultrasonic C-scan contains information about the weld structure, possible voids occurring in the weld zone, and penetration depth of the electron beam. This can be observed in Fig. 8, showing a C-scan of an EB weld with natural defects. The coarse weld structure is clearly pronounced in the C-scan. The weld root is irregular due to the variation in the penetration depth. Dark spots indicate reflections from natural defects (voids).

The ultrasonic array technique has been continuously developed in our group to improve the detectability of voids in the EB weld. Since the material structure is coarse in the weld zone and the amplitude information is used as a detection criterion, defect indications are difficult to distinguish from ultrasonic clutter scattered from the weld structure. Different filtering techniques aimed at improving the sensitivity have been tested with limited success. The most promising are techniques resulting in improving the overall resolution by application of synthetic aperture focusing combined with temporal deconvolution.

The second problem encountered here is a reduced sensitivity close to the outer wall, that is, exactly in this zone where the highest sensitivity is required. This phenomenon is observed due to spurious reflections from the corner formed by the canister wall and the boundary between the weld zone and parent material. This problem will be solved by application of the third NDT method – eddy current inspection.

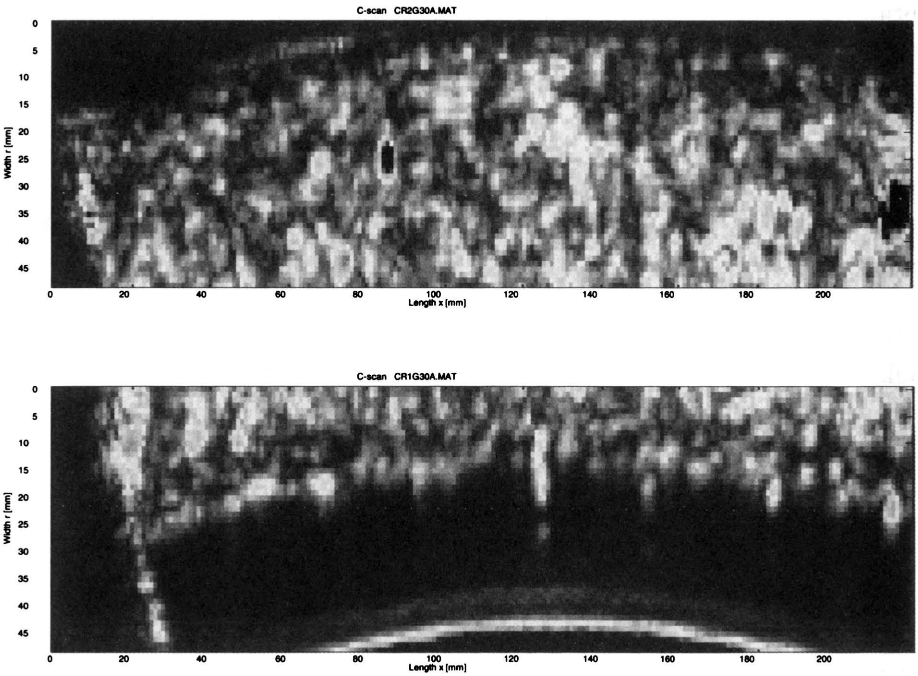


FIGURE 8. C-scan of an EB weld in copper canister. The upper and lower panel show the outer and inner part of the weld, respectively. Dark area below the weld root corresponds to unwelded parent material.

5. Eddy current inspection

Required sensitivity for subsurface voids can be achieved using low frequency, deep penetrating eddy current. The eddy current probe will scan the outer canister surface after machining (milling the material overflow from the welding operation) in the configuration shown in Fig. 9.

Application of eddy current for detecting deep subsurface defects in copper is a kind of challenge due to high electrical conductivity of copper that results in a low standard penetration depth for eddy currents. A deep penetrating, well-balanced probe fed with a low test-frequency has to be used to achieve this goal. A specially designed double differential EC probe from Leotest in Lvov has been used with the test-frequency below 1 kHz [5]. It has been proven in our laboratory that this type of probe is capable of detecting 1mm diameter voids at the depth up to 4 mm. As an example, in Fig. 10 we present probe's response to 0.8, 2 and 3 mm holes in copper plate at the depth 3 mm.

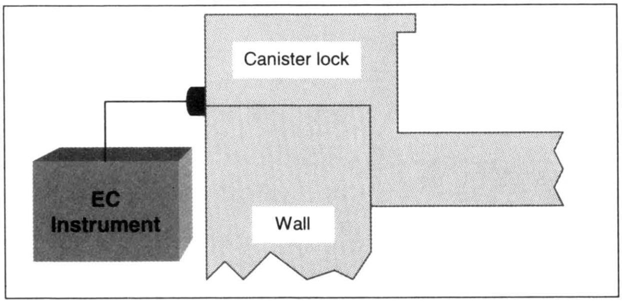
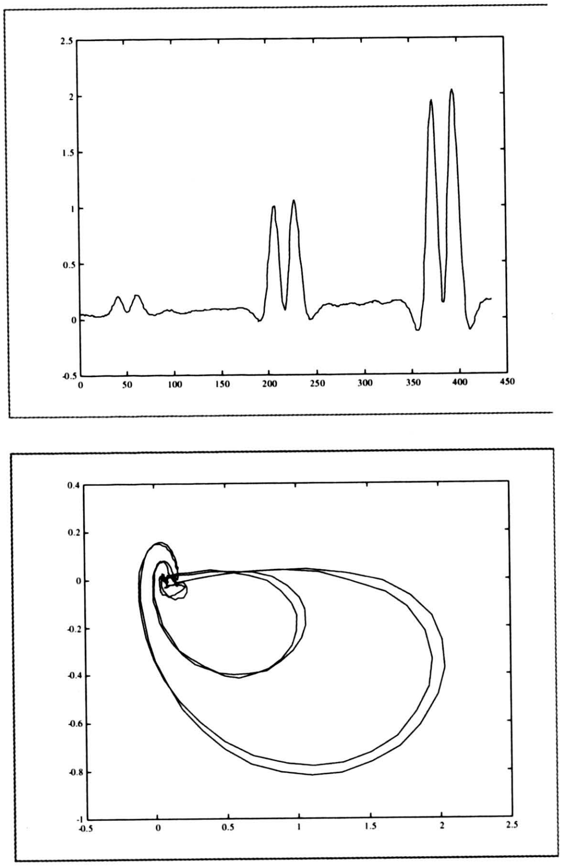


FIGURE 9. Setup of the eddy current inspection. Canister is turned and the EC probe scans its outer surface.



(a)

(b)

FIGURE 10. C responses of the probe to a 0.8, 2 and 3 mm holes in copper plate at the depth 3 mm. (a) EC pattern at impedance plane. (b) In-phase component of the complex signal.

We have shown that that defect sizing is a relatively simple task that consists of estimating defect depth based on the phase angle of its response and using EC amplitude for estimating defect diameter [5].

6. Concluding remarks

NDT methods used for the assessment of electron beam welds sealing copper canisters for spent nuclear fuel from the Swedish nuclear power plants have been reviewed in the paper. Three independent NDT techniques have been developed and tested in this application: X-ray radiography, ultrasound and eddy current. The use of three NDT methods increases the overall inspection reliability since the techniques are complementary concerning defect detecteability and sizing.

Due to the use of strong X-ray source and a digital detector the radiography is able of penetrating the whole weld volume and yields high-resolution images.

Ultrasonic inspection employs phased array technique that provides considerable flexibility in beam-forming and a high inspection speed. Ultrasonic inspection yields clear C-scan images that facilitate localization of the detected defects.

Eddy current is capable of detecting surface breaking and subsurface defects that may have very serious consequences for canister live-length.

All methods are currently verified in the SKB's canister laboratory where full size canisters are welded. The experience gained in the laboratory will be used for designing the final canister inspection, which will be installed in the future canister factory that is to be built in Sweden in 2010.

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