# Ultrasonic Investigation of the Welding Area of Copper Canisters for Spent Nuclear Fuel

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## Abstract:

*Geological repositories will be built in several countries for the long term storage of spent nuclear fuel. Sweden and Finland, for example, foresee the encapsulation of the spent fuel assemblies in copper canisters with iron inserts to be deposited in tunnels excavated about 500 metres underground in the bedrock. During the transport of canisters and the storage in the final repository, the Continuity of Knowledge (CoK) of spent fuel must be kept. Safeguards requirements suggest the implementation of a unique identification tag on copper canisters, strongly reliable and secure against falsification attempts. This paper presents a solution for the canisters' authentication issue, using an innovative ultrasonic investigation of the internal gap between copper lid and canister tube. It provides a fingerprint strictly related to material features after the friction stir welding process. This fingerprint can be combined with the ultrasonic response of a unique code made by chamfers machined on the copper lid inner surface. The angular matching between the two fingerprints (internal gap response and chamfers' code reading) realizes a third signature more robust and reliable. A potential practical implementation of this solution is described experimentally in this paper.*

**Keywords:** copper canisters; authentication; ultrasounds; encapsulation plant; geological repository.

## 1. Introduction

The spent fuel coming from nuclear reactors is an environmental hazard and it must be safely managed according to Safety, Security and Safeguards requirements. Several countries, among which Sweden and Finland, are planning to construct geological repositories for the storage of their spent fuel. According to this new approach, the fuel will be encapsulated in copper canisters with iron inserts, deposited in tunnels 500 m underground and covered by bentonite clay. Geological repositories, in fact, would be able to insulate the spent fuel from human beings and the environment without requiring supervision or maintenance after closing [1]. Figure 1 shows the structure of the geological repository planned to be built in Sweden.

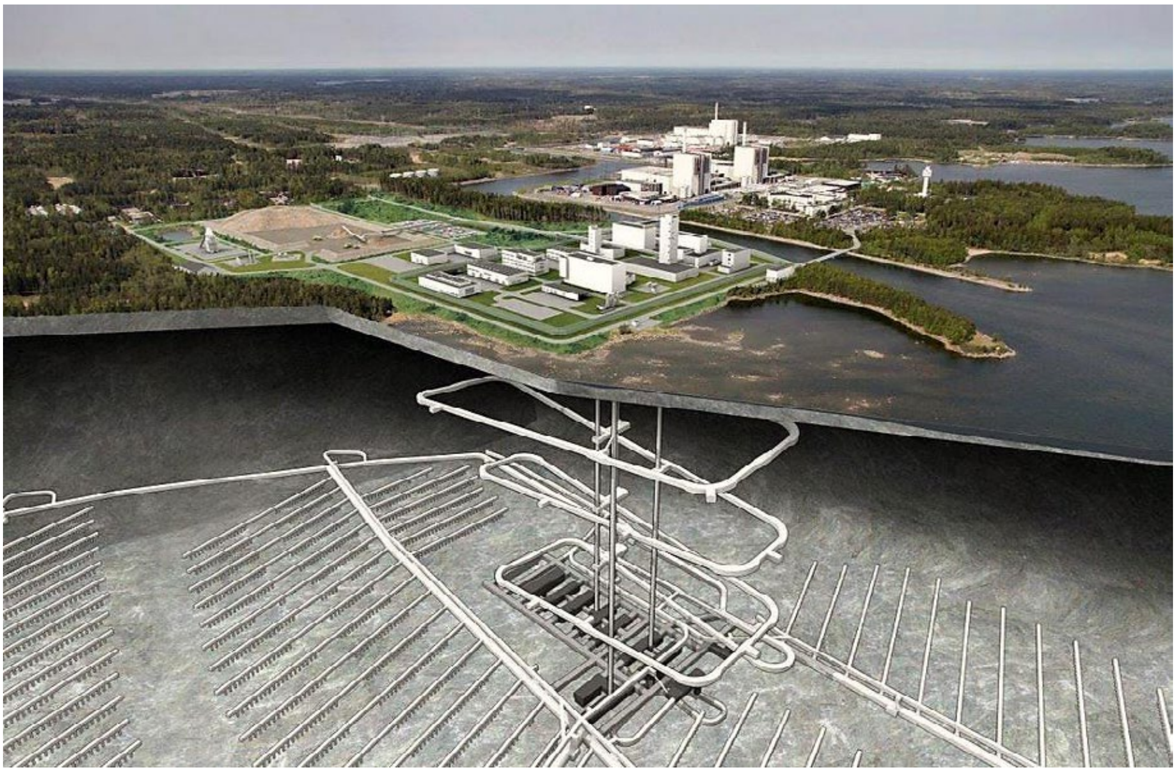

**Figure 1.** Design of the geological repository proposed for Sweden with its 66-kilometre of tunnels. Source: SKB.

The fuel stored in underwater storage ponds is moved to the encapsulation plant where it is introduced in copper canisters. Canisters are then sealed by Friction Stir Welding (FSW) then, for Sweden, they are inserted into transport casks sent by ship to the final repository. For Finland, the encapsulation plant will be built just above the geological repository, so no transport casks needed. The analysis of threat, diversion strategies and safeguards requirements for a geological repository stressed the importance of keeping the Continuity of Knowledge (CoK) of spent fuel during transport from the encapsulation plant to the final storage or during the storage of canisters before the deposition in tunnels. Containment and Surveillance (C/S) measures have to be implemented in the encapsulation process and on the transportation cask [2]. Moreover, the International Atomic Energy Agency (IAEA) and the European Atomic Energy Community (EURATOM) recommended to use canister identification to support the CoK of spent fuel [3].

Engraving of the canister's external surface is a practical and simple solution but may affect the long-term integrity of the container and then must be carefully considered. Moreover an engraving on the external surface can be easily reproduced and then it is not secure against falsification attempts. Considering alternative solutions, the most common technologies used for tagging of nuclear items include seals, Radio Frequency Identification (RFID) tags, SERS (Surface-Enhanced Raman Scattering) -Active Nanoparticle Aggregates tags, Tungsten-based identifier, reflective laser scanning tags, reflective particle tags (RPT) and ultrasonic systems [4]. All these techniques could potentially provide a unique identification for canisters but only ultrasounds could satisfy both the requirements of identification and authentication at the same time [5]. In 2015 the SSM asked the Joint Research Centre (JRC) of the European Commission for a feasibility study on copper canisters identification by ultrasounds. This research has been carried out by the Seals and Identification Laboratory (SILab) of the JRC in Ispra (Italy) in collaboration with the Department of Information Engineering at the University of Florence (Italy). The SILab has a long time experience on ultrasonic techniques applied on bolt seals with artificial cavities made of stainless steel washers with cavities, giving a fingerprint from the reflection of unique patterns [6]. Concerning copper canisters, the geometry and dimension of the container are much bigger than a seal; therefore, an adaption of the ultrasonic methods should be implemented.

The following chapters describe the development of the new solution for the identification and authentication of copper canisters by ultrasounds. The first part illustrates the basic idea of the new method and the preliminary studies carried out on copper specimens to verify the propagation of ultrasounds in the material. Afterwards the experimental tests carried out at the SKB's Canister laboratory in Oskarshamn (Sweden) are reported and results are analysed.

## 2. Ultrasonic authentication of copper canisters

The method used for labelling copper canisters must be tamper indicating by a unique identity (identification) and must provide evidence of counterfeiting or duplication (authentication). For this purpose, the method developed by the SILab is based on the combination of two fingerprints, one artificial and one natural. The first is realized by machining chamfers on the inner surface of the copper lid, creating a unique code readable from the outside by an inclined ultrasonic transducer with water poured on the lid. The study of this identification method has been already described by the authors in [7] and [7]. Results of simulation and experimental tests made on a reduced scaled copper lid with chamfers, pointed out the possibility to acquire ultrasonic echoes with a good signal to noise ratio. The code made by chamfers is then clearly detectable by ultrasounds but it is not robust enough in case of falsification or duplication attempts. Therefore, an authentication signature is necessary to verify the originality of canisters. This paper is focused on the study of an authentication method based on the ultrasonic investigation of the natural fingerprint, intrinsically contained in copper canisters after the FSW process. The general idea of the method and its validation is described in the following paragraphs.

### 2.1 The method

The nuclear spent fuel to be stored in geological repositories is preserved by an insert of nodular cast iron that gives mechanical stability and an outer copper shell which provides protection against corrosion. The copper canister is about 5 metres in length and 1 metre in diameter [9]. The minimum copper thickness is 50 mm to fulfil mechanical design requirements [10] (Figure 2).

After the encapsulation of the fuel, a lid is welded onto the canister by FSW. A rotating tool is plunged between the

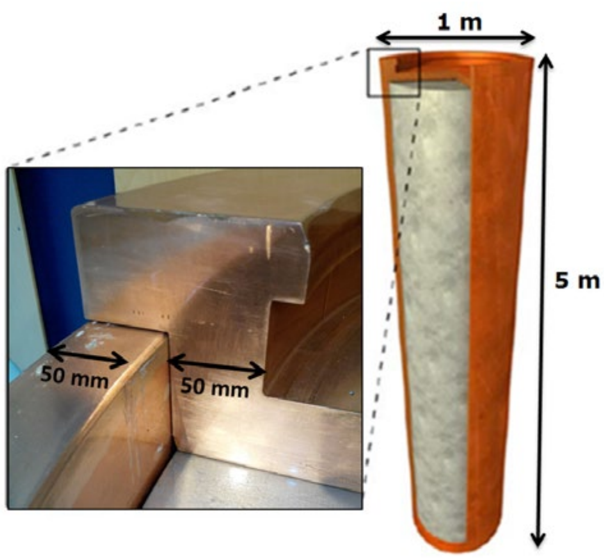


**Figure 2.** Copper canisters dimensions.

pieces to be welded and makes the material plastic by the heat generated with the friction. During the tool movement the two surfaces are stirred together and a joint is realized [11]. The weld joint design includes a gap between the lid and the canister. This gap represents a discontinuity in the material, detectable by an ultrasonic transducer placed beneath the welding line (Figure 3).

The amplitude response acquired by the ultrasonic testing around the circumference of the welded canister could be used as a fingerprint, unique and different to each canister.

Before the evaluation of the amplitude response of the welding area of a full scale copper canister, preliminary studies were carried out on copper flanges, i.e. slices of the copper lid already welded onto the tube. The first tests implemented by the manual displacement of a contact transducer (V111-RM Fingertip Contact Transducers - Panametrics) revealed a series of fingerprints such as those illustrated in Figure 4. The probe is moved along arcs 380 mm wide positioned at different heights (h=25, 23, 21, 19, 17, 15 mm) from the bottom surface of the lid (see Figure 3).

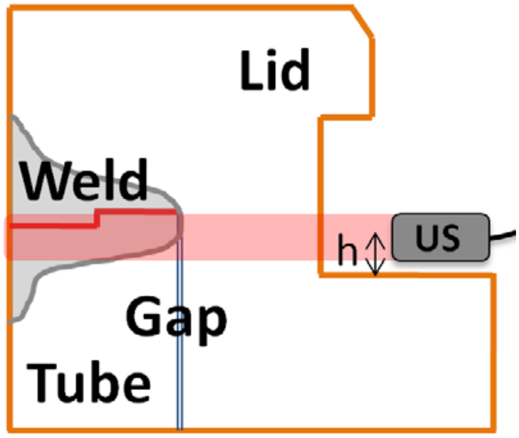


**Figure 3.** Position of the ultrasonic transducer for the investigation of the gap between copper lid and tube.

The variation of the ultrasonic amplitude echo is more marked at h=15 mm where the gap is clearly detectable. Moving the probe at higher positions the amplitude of the received echo is lower. This means that the gap is disappearing from the focus of the probe and the interface between lid and tube is perfectly welded. As a consequence, the presence of a discontinuity in the material detectable by ultrasounds is demonstrated. However, it is important to remember that flanges are just laboratory samples and that the variation of patterns in a real canister coming from a production-like process could be lower. Therefore experimental tests on full scale lids already welded onto tubes must be implemented to verify the accuracy and repeatability of the method. For this purpose, the manual scanning of the sample is replaced by a reader prototype hosting a motor for an automated scanning. The description of this new system called *IDA reader* is reported in the following paragraph.

### 2.2 The IDA Reader

The IDA (IDentification and Authentication) reader is a device for the identification and authentication of copper canisters. The first prototype realized is only dedicated to the acquisition of an authentication fingerprint. The system is composed by a reader, a control box and a computer (Figure 5). The reader consists of three supporting arms made on steel, centred on the lid, and a motor devoted to the rotation of a rod holding the ultrasonic transducer (Olympus V311 with 10 MHz central frequency and 8.4 inches spherical focused). The probe is kept perpendicular to the lid surface and its distance can be adjusted from 50 mm to 25 mm, while height (h) from 35 mm to 14 mm from the bottom of the lid. The box hosts an electronic board connected to an US-Key module (Lecoeur Electronique) controlling the motor's rotation and the transmission/reception of the ultrasonic signal. Lastly the

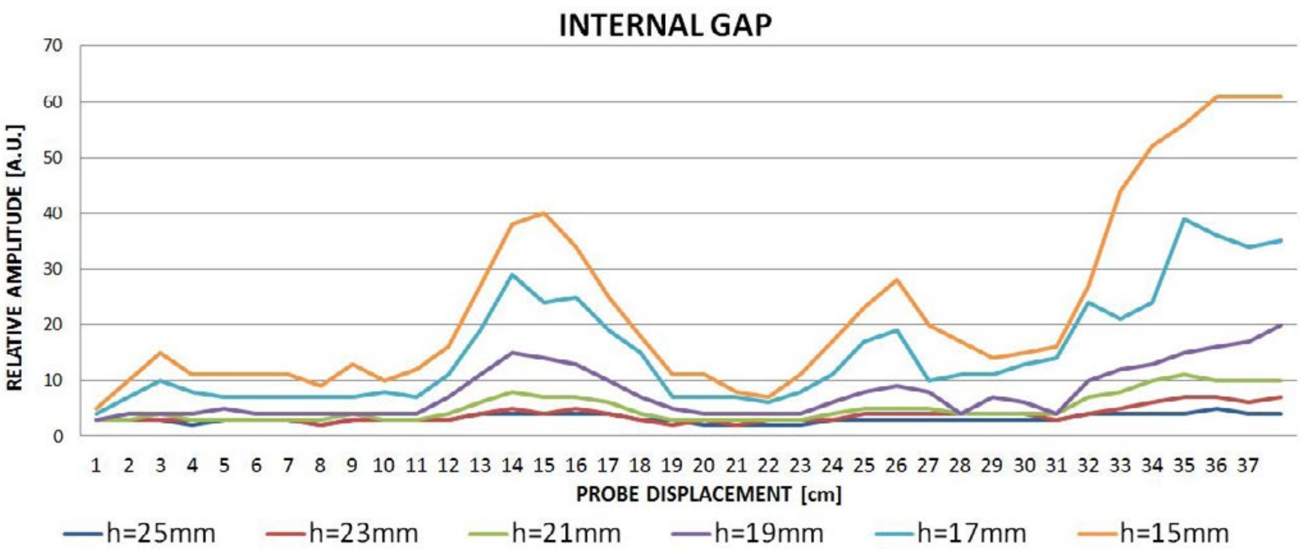


**Figure 4.** Relative amplitude responses of the internal gap between copper lid and tube.

computer displays the software interface for the setting of testing parameters and the signal processing.

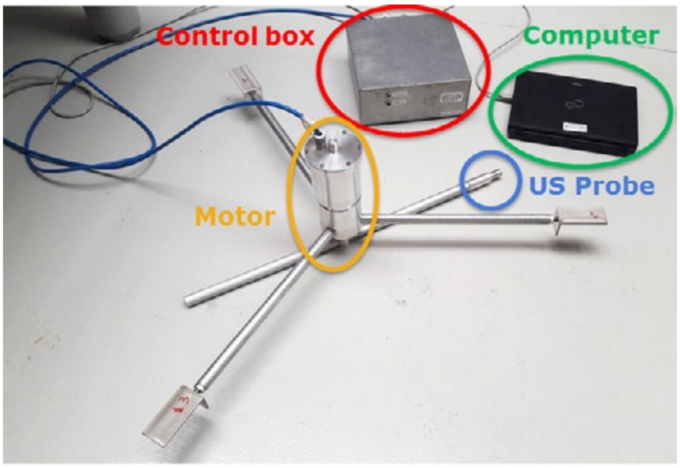


**Figure 5.** IDA reader prototype.

The software interface is composed by four different tabs. The first tab allows the setting of the main measurements parameters and the three gates (time windows) of interest, where echoes are expected. The second and third tabs are then focused on the acquisition of the internal gap fingerprints. The last part is centralized on the signal processing. In particular, the correlation index between two fingerprints selected from the database can be calculated and the two curves can be displayed shifted and overlapped on a chart.

The first test of the reader is carried out at the SILab facility on copper flanges arranged around a circumference reproducing the same geometry of a real copper lid welded on a tube. The three arms of the reader should be perfectly parallel to the bottom of the lid to keep the probe perpendicular to copper interface during revolution. The scan time is roughly 4 minutes, corresponding to a 360° rotation of the probe around the circumference. Before starting with tests, the temperature of water is measured through an infrared digital thermometer and the probe distance and height are set by a calliper. Depending on temperature and probe position, different time windows shall be settled in the acquisition software to ensure a good reception of the ultrasonic echoes. The set-up of measurements is shown in Figure 6.

Several tests were carried out changing the angular position of the reader's arms above flanges and the analysis of acquired echoes revealed a very high correlation between fingerprints, whether acquired without changing the set-up or adjusting the reader positions above flanges.

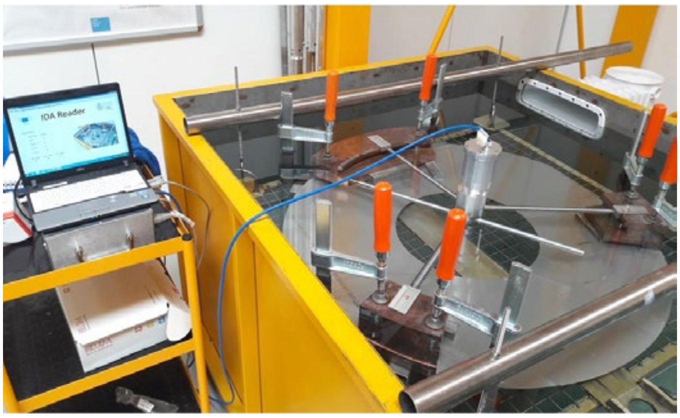

**Figure 6.** Set-up of measurements.

## 3. The experimental testing

The experimental testing of the ultrasonic method for the authentication of copper canisters was done by the ultrasonic investigation of two copper lids already welded onto tubes at the SKB's Canister Laboratory. The aim of these inspections was to verify the detectability of a fluctuating fingerprint due to variations in the material after welding. Moreover, the repeatability of the method should be confirmed by the high correlation indexes between multiple acquisitions with the IDA reader. This chapter describes all the measurements implemented and their results.

### 3.1 The ultrasonic testing at the SKB's Canister laboratory

The SKB's Canister Laboratory, situated in Oskarshamn's port, is the centre for the development of technologies that will be used for the encapsulation of spent fuel in copper canisters. The laboratory houses the SKB's prototype of the welding machine, manufactured by ESAB and used for the FWS of the lids to the canisters [12].

The ultrasonic inspections with IDA Reader were carried out on two samples of copper lids already welded onto tubes (FSWL 121 and FSWL 122). The geometries of the two original lids were slightly different therefore the uniqueness of fingerprints could not be checked. However comparisons between received echoes are useful to evaluate the efficacy of the ultrasonic method. Copper samples are placed in a tank with water (Figure 7) and four labels are arranged at 90° from each other on the upper surface of the lid to create a reference pattern for measures.

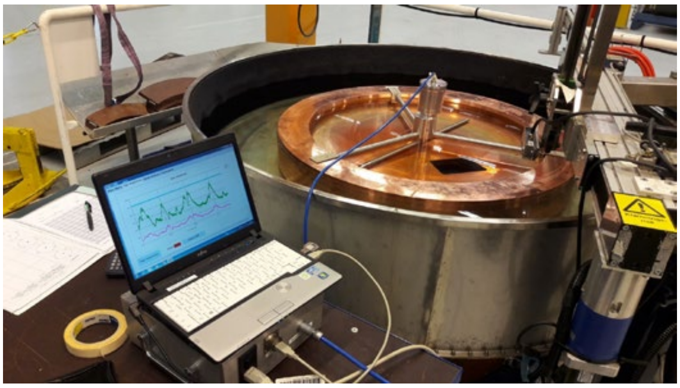

**Figure 7.** Experimental testing of the IDA reader at the SKB's Canister Laboratory.

In this way, different acquisitions are carried out changing the arms positions around the circumference. The series of measurements implemented is shown in Figure 8. For each position A, B, C, D, the height of the transducer is changed from 15 mm to 21 mm with a step of 2 mm. Through the variation of the reader position, it is possible to verify the reader ability to perform repeatable measurements. The adjustment of probe heights, instead, aims to detect which is the variation of the ultrasonic amplitude response in the entire welding area.

### 3.2 Analysis of results

The analysis of the data acquired during the ultrasonic investigations is presented in this paragraph. The most meaningful fingerprints are reported and compared to identify the main features. The first result illustrated concerns the investigation of the FSWL 122 at 15 mm of probe height. The temperature of water during the test was 18°C, the probe distance 50 mm and the gain of the electronic receiver was 37 dB. The chart below (Figure 9) shows the ultrasonic amplitude response related to two different gates (gate 2: 82-97μs and gate 3: 102-117 μs), on 360° of the lid circumference. The signal in blue is the amplitude response due to the reflection on the internal gap. In purple, instead, it is shown the double reflection of the previous signal that is temporally located at the same time windows than the external wall echo (because thicknesses of tube and lid in this region are both 50 mm). The vertical line in red marks the starting point of the weld (the entry point of the welding tool).

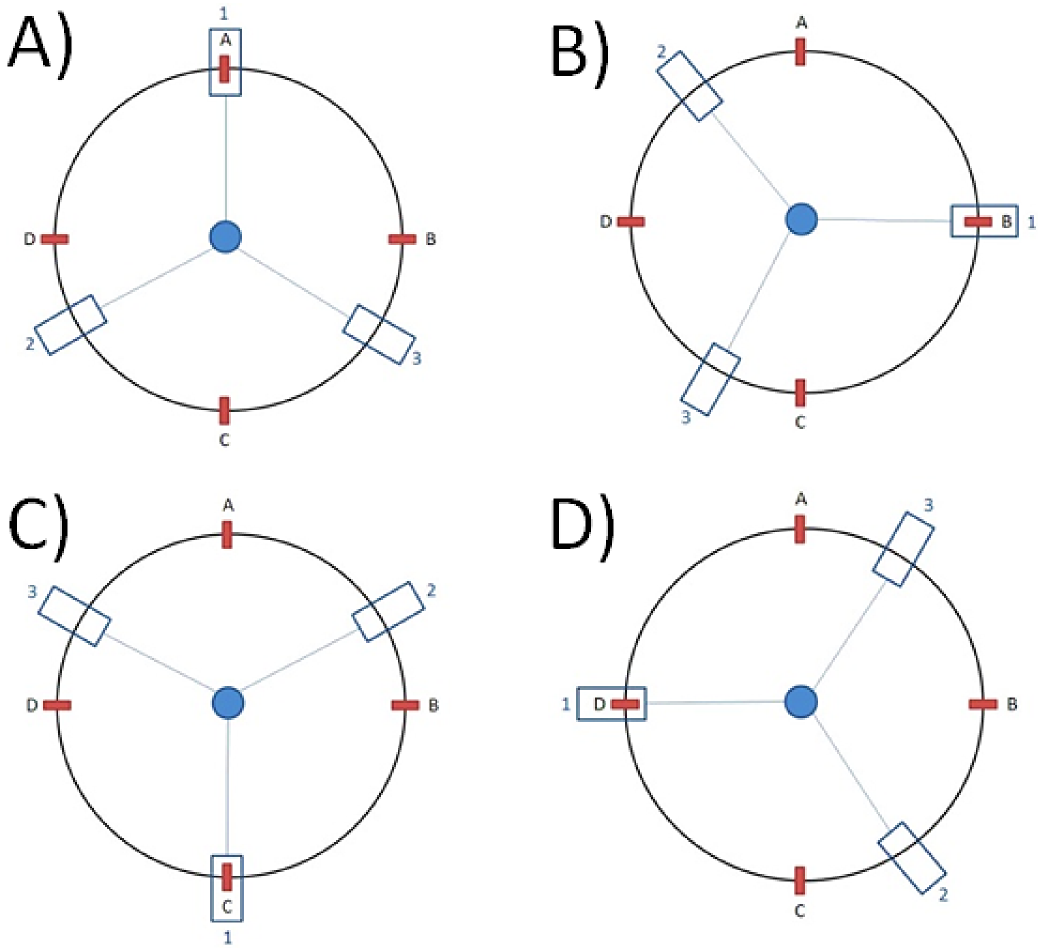


**Figure 8.** Sequence of measurements implemented on copper samples.

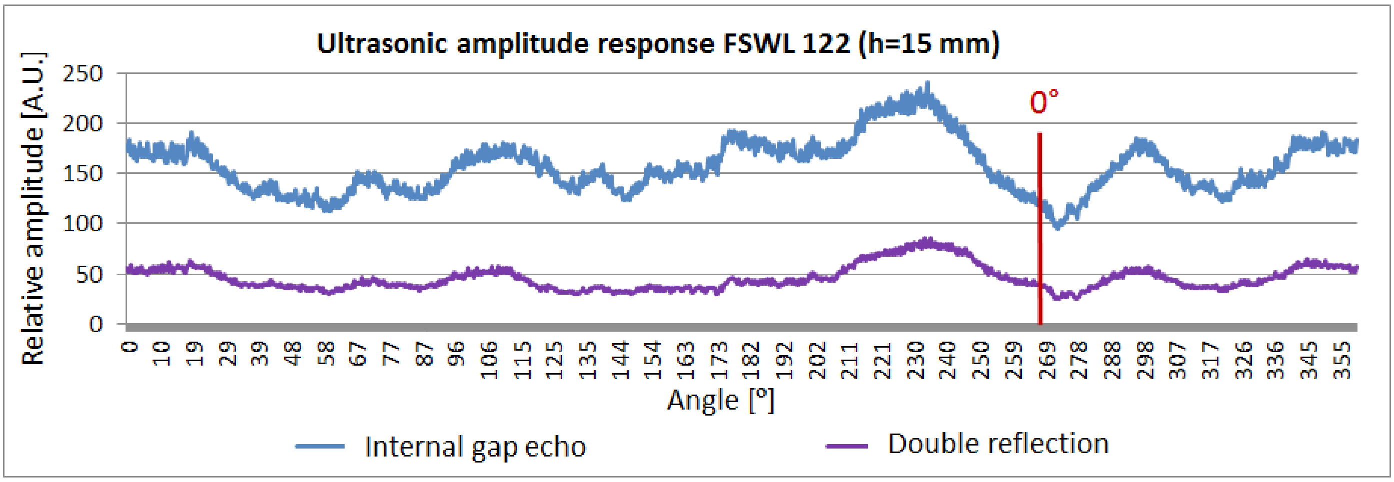


**Figure 9.** Ultrasonic amplitude response of FSWL 122 at 15 mm height.

The variation of the signal could be related to the different grain size in the material that generates a different attenuation pattern around the lid circumference. Several measurements are implemented changing the position of the reader above the sample and the correlation between different acquisitions is high. Therefore the repeatability of signatures is verified and signals are stable if we consider a constant water temperature, even though influence of water temperature can be easily compensated.

In order to verify that the echo in purple was exactly the repetition of the first in blue, an inspection simulation with CIVA software is implemented (Figure 10). As a result, the simulated A-signal exhibit three main echoes: the first related to the interface water/copper, the second due to the reflection on the internal gap (corresponding to the blue trace) and then a second reflection whose features (amplitude and time of flight) agrees with our results (purple trace).

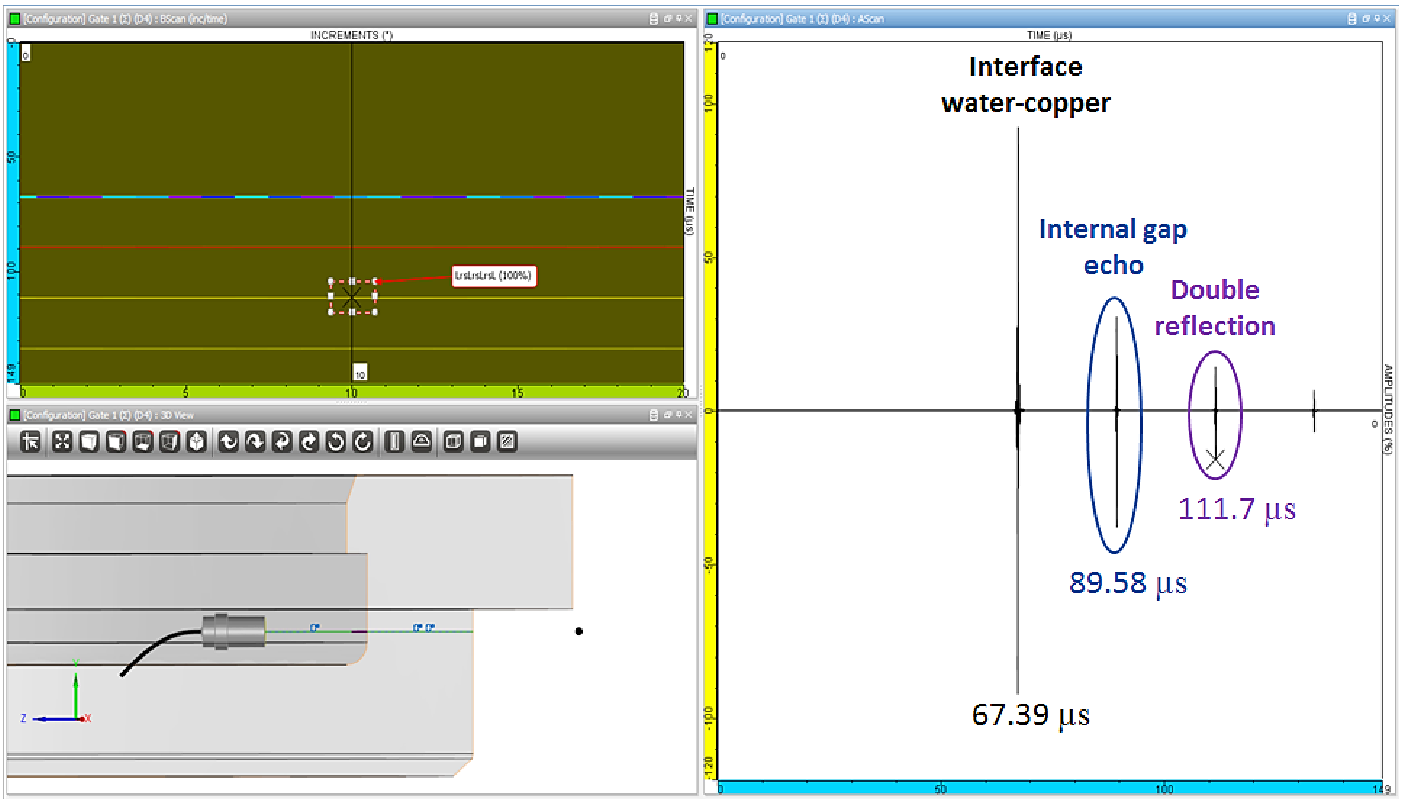


**Figure 10.** Inspection simulation implemented by CIVA software for the verification of the time of flight of the double reflection on the internal gap.

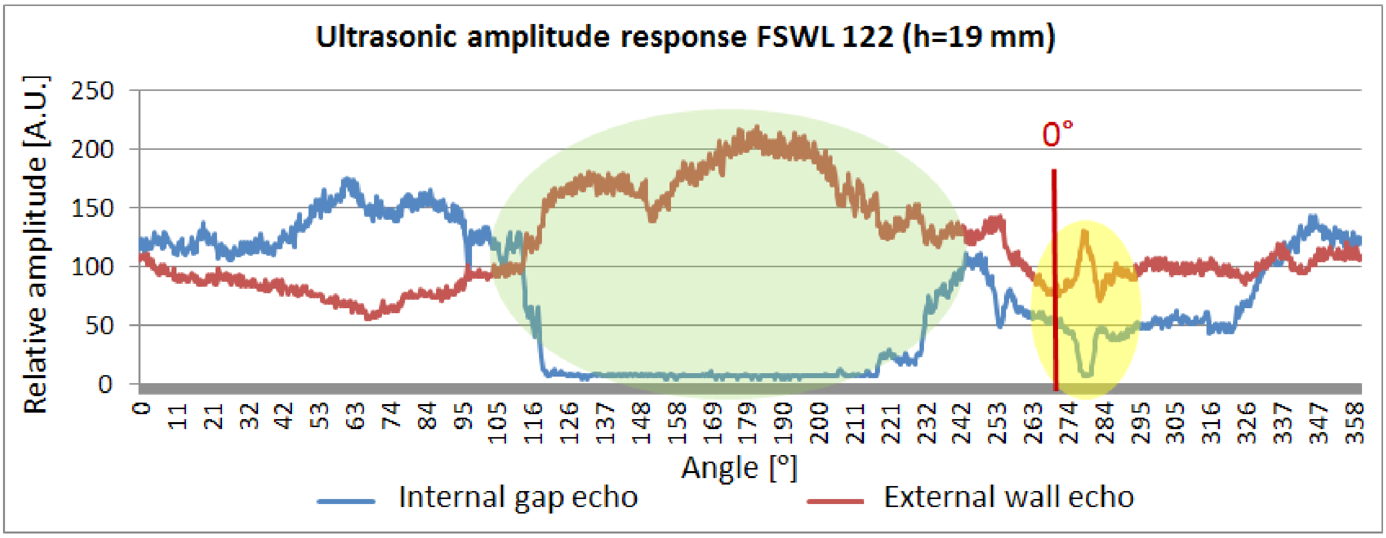


**Figure 11.** Ultrasonic amplitude response of FSWL 122 at 19 mm height.

The probe is then moved at height 17 mm, 19 mm and 21 mm. The next picture (Figure 11) shows the ultrasonic investigation of the lid at 19 mm of height. This time in blue is reported the amplitude response of gate 2 due to the internal gap reflection and in red the amplitude response of gate 3 that corresponds to the external wall echo. In fact, when the weld joint is perfect, ultrasounds can penetrate in the material without reflection up to the last interface that is the external wall of the canister. As shown in the chart, when the external wall gives a high echo, the internal gap echo is practically zero (green area). The inversion of signals interests an arc of about 100°.

It is interesting to underline the presence of another signal inversion, highlighted in yellow, which could correspond to the point where the welding tool passes two times during the welding process. According to Figure 12, in fact, only when all the parameters are stable, the tool descends at the welding line level and starts the weld (point 4). After 360°, it passes by the starting point and then return back (point 5). This hypothesis is also in accordance with the position of the entry point (vertical red line in the chart) of the welding tool.


**Figure 12.** Welding tool rotation and sequences in the welding cycle: 1) acceleration sequence, 2) downward sequence, 3) joint line welding, 4) overlap sequence and 5) parking sequence.

The ultrasonic investigation of the second sample, FSWL 121, generated similar results. In particular Figure 13 reports the internal gap echo and the external wall echo received by the transducer placed at 21 mm of height. As the previous case, an inversion of signals is clearly detectable (yellow area) and probably represents the crossing point of the welding tool (point 4 in Figure 12).

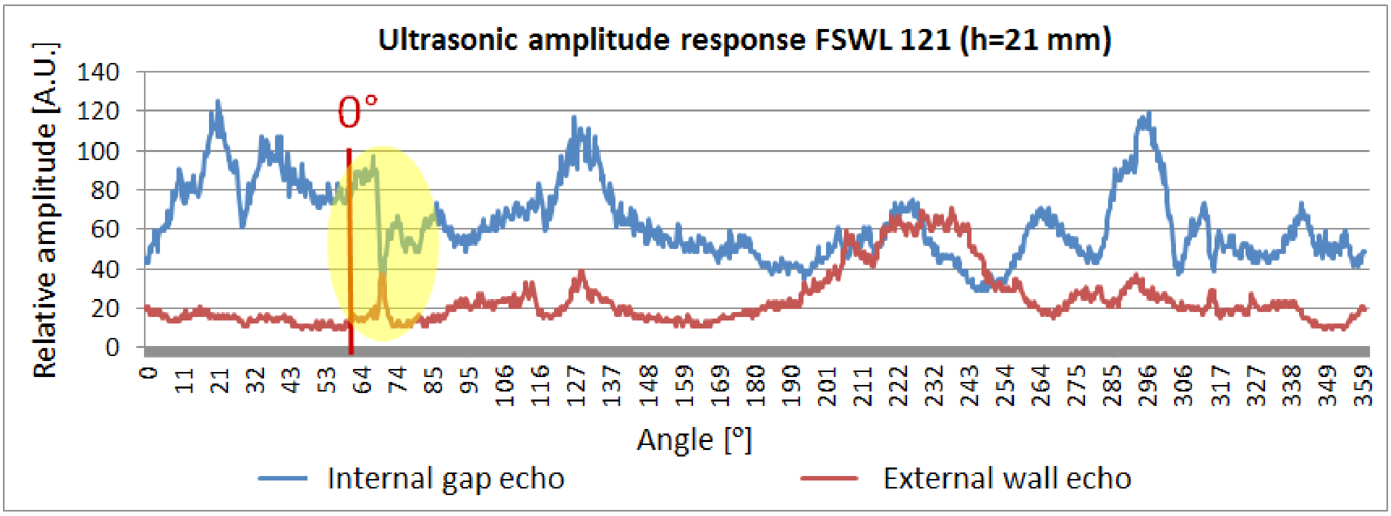


**Figure 13.** Ultrasonic amplitude response of FSWL 121 at 21 mm height.

| | FSWL 121 | | | | FSWL 122 | | | |
|---|---|---|---|---|---|---|---|---|
| | **h=15mm** | **h=17mm** | **h=19mm** | **h=21mm** | **h=15mm** | **h=17mm** | **h=19mm** | **h=21mm** |
| Correlation indexes between different acquisitions | 0.96 | 0.80 | 0.65 | 0.66 | 0.80 | 0.92 | 0.96 | 0.81 |
| | 0.97 | 0.79 | 0.80 | 0.75 | 0.64 | 0.92 | 0.88 | 0.72 |
| | 0.95 | 0.82 | 0.62 | 0.47 | 0.89 | 0.97 | 0.87 | 0.78 |
| | 0.95 | 0.83 | 0.99 | 0.79 | 0.88 | 0.97 | 0.83 | 0.81 |
| | 0.96 | 0.98 | 0.75 | 0.67 | 0.93 | 0.95 | 1.00 | 0.92 |
| | 0.96 | 0.80 | 0.86 | 0.68 | 0.83 | 0.91 | 0.97 | 0.84 |
| | 0.98 | 0.61 | 0.63 | 0.47 | 0.71 | 0.90 | 0.89 | 0.97 |
| Average value | 0.96 | 0.80 | 0.76 | 0.64 | 0.81 | 0.93 | 0.91 | 0.84 |

**Table 1.** Correlation indexes between acquisitions at 15-17-19-21 mm of height.

Following the analysis of echoes at different heights, fingerprints are compared to verify the repeatability of measures. The Pearson's correlation coefficient is calculated between acquisitions carried out at the same height. The resulting values of correlation indexes are collected in Table 1, and the average value for each height is evaluated. Results put in evidence that the IDA reader is able to acquire ultrasonic signals with a good precision because correlation indexes are higher than 0.8 in most of the cases. However for FSWL 121, measurements acquired at 19 mm and 21 mm present lower values, probably due to an incorrect fixing of the rod holding the transducer.

## 4. Conclusions

The identification and authentication of copper canisters is of upmost importance to guarantee the Continuity of Knowledge of spent nuclear fuel during transport, storage and deposition in the geological repository. In the past, different technologies were assessed for the labelling of spent fuel casks and, among them, ultrasonic systems would be the best option [13]. The SILab of the Joint Research Centre in Ispra developed an ultrasonic method for copper canister identification and authentication. The identification could be realized by the machining of chamfers on the inner surface of the lid, forming a unique code readable by an ultrasonic transducer immerged in water, rotating around the lid circumference. The authentication, instead, could be verified by the ultrasonic inspection of the welding area between lid and tube after Friction Stir Welding. Following the description of the authentication method, this paper reports the experimental tests carried out at the SKB's Canister Laboratory in Oskarshamn. For this purpose, a new reader prototype called IDA reader is developed. The fingerprints acquired during the visit in Sweden are then analysed and compared. The analysis of signals revealed a quite marked variation of the amplitude of the internal gap echo. The uniqueness of fingerprints could not be verified because of the differences in copper lids geometries; however several featured points were identified on fingerprints. Moreover, the repeatability of fingerprints is proved by making different tests on the same samples. Nevertheless, additional inspections on final welded copper samples with the selected geometry of the lid must be carried out in order to verify uniqueness and identify distinctive features on welding areas. Meanwhile, the ultrasonic method will be presented to international safeguards authorities which would give their feedback on the proposed solution.

## 5. Acknowledgements

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