ULTRASONIC METHOD TO KEEP THE CONTINUITY OF KNOWLEDGE OF SPENT NUCLEAR FUEL FROM THE ENCAPSULATION PLANT TO THE GEOLOGICAL REPOSITORY

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Abstract

Nowadays several countries are planning to store nuclear spent fuel in long-term geological repositories. The fuel will be preserved for thousands of years inserted in copper canisters with iron inserts. In Sweden, after the encapsulation of the fuel, canisters will be welded and transported to the geological repository for the deposition in tunnels. During transport, the Continuity of Knowledge (CoK) of spent fuel must be kept. An option could be the identification of canisters. Traditional tagging methods do not fit all the requirements foreseen in this application and then alternative ideas should be developed. The method proposed by the Joint Research Centre of the European Commission, in collaboration with the University of Florence (Italy), could guarantee not only a unique label for each canister but also security against falsification attempts. The idea is to combine two fingerprints: the first (artificial signature) related to a configuration of chamfers arranged around the lid circumference and the second (natural or intrinsic signature) due the variation of the internal gap between lid and tube after the welding process. The geometry and position of chamfers are designed to maximize the ultrasonic echo without affecting too much the canister structure and minimize the influence on the mechanical properties of the canisters. The ultrasonic amplitude response (identification fingerprint) acquired by a rotating high frequency (10 MHz) transducer with a fixed height is strictly related to chamfers disposition and then it is unique for each container. However, in order to verify the originality of canisters, the internal gap between lid and tube is investigated. The ultrasonic response due to the inspection of the welding area is a “natural” fingerprint (authentication fingerprint) for canister because it is connected to the welding process and material properties. The identification and authentication of fingerprints can be combined by angular matching to increase the robustness of the method. The description of the method and the development and testing of the ultrasonic reading system are reported in the paper.

1. INTRODUCTION

The long-term storage of nuclear spent fuel in geological repositories has introduced the need to promote new containment and surveillance (C/S) measures to maintain the Continuity of Knowledge (CoK) during encapsulation, transportation and disposal of the fuel. In Sweden, the Swedish Nuclear Fuel and Waste Management Co. (SKB) developed a multi-barrier system to preserve spent fuel for thousands of years. After a storage period at the Central Interim Storage Facility (Clab) in Oskarshamn, the spent fuel coming from nuclear reactors is lifted from pools, dried and moved to the encapsulation plant (that will be built next to the Clab). There, fuel assemblies will be is inserted in copper canisters with iron inserts and then welded by Friction Stir Welding (FSW). After closure, canisters will be transported in transport casks to the geological repository in Forsmark (Fig.1). At the repository, canisters will be located with a deposition machine in tunnels excavated approximately 500 m underground and then covered by bentonite clay. In this way, spent fuel would be stay isolated from human beings and environment for thousands of years. The total amount of canisters to be deposited is estimated to be around 6000, with an average of one canister per day during roughly 40 years [1]. The final disposal of spent nuclear fuel in geological repositories presents new challenges for nuclear safeguards: conventional approaches based on nuclear material accountancy (NMA) and C/S measures should be adapted and expanded to guarantee a high security level throughout all the process.

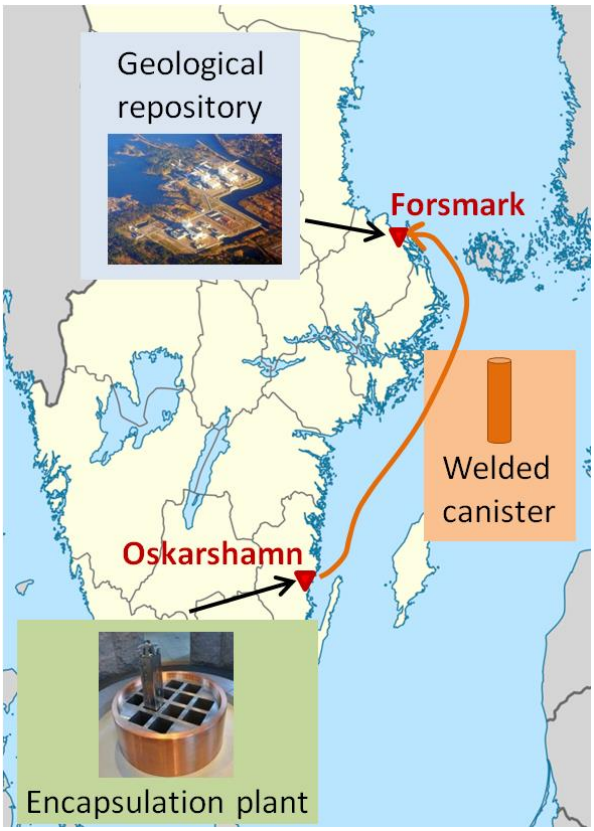

FIG. 1. Copper canisters path after the encapsulation of spent fuel in the Swedish system.

Once canisters are stored in tunnels, the re-verification of NMA in case of C/S measures failure is practically impossible. Therefore, the International Atomic Energy Agency (IAEA) and the European Atomic Energy Community (EURATOM) suggest the implementation of redundant or dual C/S systems which are independent in terms of tampering or failure mode, in order to reduce the possibility of loss of CoK [2-3]. Surveillance devices could be used inside facilities to monitor the flow and detect potential undeclared accesses, while tamper-indicating seals could be applied on transport casks to ensure that canisters have not been compromised during transport from the encapsulation plant to the geological repository. However, in addition to seals, canisters' identification could be used as a complementary C/S measure to recover CoK in case of losses. Outside facilities boundaries, in fact, copper canisters are more vulnerable to diversion and then verifying canisters' identity and integrity could be advantageous. External engraving on canisters' surfaces could damage a canister's integrity, triggering a corrosion process. Therefore, alternatives tagging solutions should be developed to identify uniquely each canister (identification fingerprint) and assess its originality (authentication fingerprint). A comparison between potential tagging technologies already used in the nuclear field can be found in [4].

For this purpose, in 2015 the Swedish Radiation Safety Authority (SSM) asked to the Joint Research Centre of the European Commission (JRC) for a feasibility study regarding the identification of copper canisters. Therefore, the Seals and Identification Laboratory (SILab) of the JRC, in collaboration with the Ultrasound and Non-Destructive Testing Laboratory of the University of Florence (Italy), developed a new ultrasonic method for copper canisters identification and authentication. The SILab has a many years' experience in developing stainless steel ultrasonic seals for the identification and verification of nuclear casks for underwater and dry storages. Seals include a unique identity with artificial cavities which realize a unique random pattern, readable by ultrasounds [5-6]. Based on the same ultrasonic technologies, an innovative method for canisters' identification and authentication is realized. The description of the whole tagging system and its experimental validation is reported in the following paragraphs. Moreover, advantages and disadvantages of the method are discussed, highlighting further steps to improve the ultrasonic system.

2. THE ULTRASONIC IDENTIFICATION AND AUTHENTICATION OF COPPER CANISTERS

The identification of a copper canister could be potentially realized by different technologies, but its authentication is more demanding. A copper canister external surface is not inherently tamper-indicating and then an identification system should be able to make evidence of falsification or duplication attempts. Moreover, it should be resistant to harsh environment and should not affect canisters integrity (avoiding corrosion effects). In addition, a portable device, easy to use and with reduced cost is preferable [7]. According to these requirements, the SILab, in collaboration with the University of Florence, developed a new approach for copper canisters' identification and authentication using ultrasounds. This method is based on the acquisition of two fingerprints: on the one hand, the ultrasonic amplitude response of a series of chamfers, machined on the inner surface of the copper lid; on the other hand, the intrinsic fingerprint of the welding area between copper lid and tube.

2.1. The identification

The identification method for copper canisters can be seen as an adaptation of the concept already developed by the SILab for seals. The idea is to drill cavities in the material in order to realize unique patterns, readable by an ultrasonic transducer. Copper canisters are big cylinders, nearly 5 m high and 1 m in diameter. Each container is composed by a tube and a lid, welded together by Friction Stir Welding (FSW). Since canisters should prevent the dispersion of nuclear material, their minimal copper thickness must be 50 mm (considering also welds). According to the ultrasonic identification method, canisters could be identified by machining chamfers, i.e. cuts of the lids' edges, in an area of the lid (yellow area in Fig. 2) where the copper thickness constraints are accomplished.

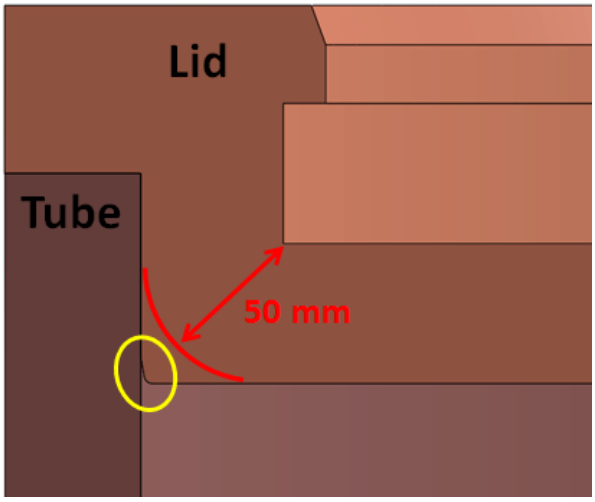

FIG. 2. Area of the copper lid (yellow circle) where chamfers could be realized since the copper thickness is higher than the limit 50 mm.

A chamfer represents a discontinuity in the copper lid that can be detected by ultrasounds. In fact, keeping an ultrasonic transducer inclined according to the Snell's law, it is possible to acquire by an immersion testing, a reflected echo in correspondence of the chamfer (Fig. 3). Consequently, machining a configuration of chamfers all around the circumference of the lid, we can create a unique code for each canister that can be read from the outside by the ultrasonic probe. The ultrasonic amplitude response acquired by a 360˚ rotation of the transducer could be used as an identification fingerprint for canisters.

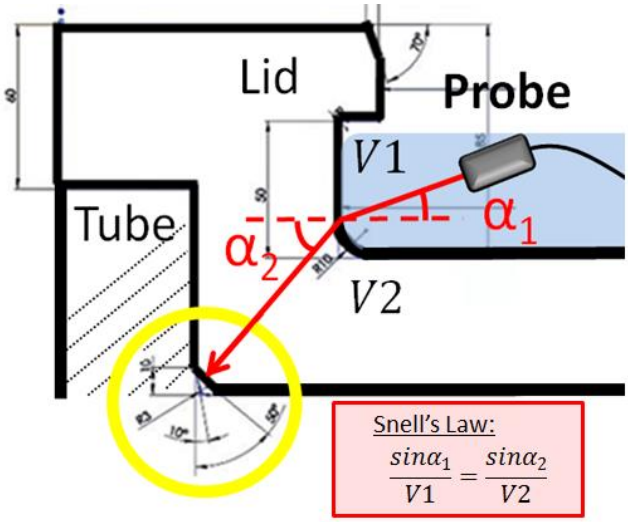

FIG. 3. Set-up of measurements for the ultrasonic investigation of a chamfer by an ultrasonic probe kept inclined according to the Snell's law.

The experimental validation of the identification concept is carried out on a copper lid mock-up with the same morphology of a full-scale lid already welded but with a reduced diameter (scaled ¼). As shown in Fig. 4, a series of chamfers 50˚ inclined, 12 mm wide and with different angular extension, are machined on the bottom surface of the lid and cavities are realized between chamfers to facilitate the manufacturing in the laboratory. Of course, the implementation of chamfers on a real full-scale lid will include only chamfers and the mechanical procedure for their realization will avoid the presence of sharp edges on the final machined lid in order to do not trigger corrosion processes.

FIG. 4. Top and bottom views of the scaled copper lid (¼) used for the experimental validation of the identification concept.

The acquisition of the ultrasonic amplitude response is carried out by a transducer placed 14° inclined in order to receive the signal reflected by chamfers, according to the Snell's law. The ultrasonic echoes are acquired rotating 360° the transducer, during an immersion testing with water as couplant. The ultrasonic amplitude response acquired by the probe is shown in Fig. 5, circled in red. The alternating evolution of the received signal agrees with expectations: there are peaks just in correspondence of chamfers and the duration of the peak is related to the angular extension of the chamfer.

The identification concept is then validated on this laboratory prototype, but another test should be carried out on a full-scale lid with chamfers having optimized geometry and disposition, to uniquely identify each container [8-10].

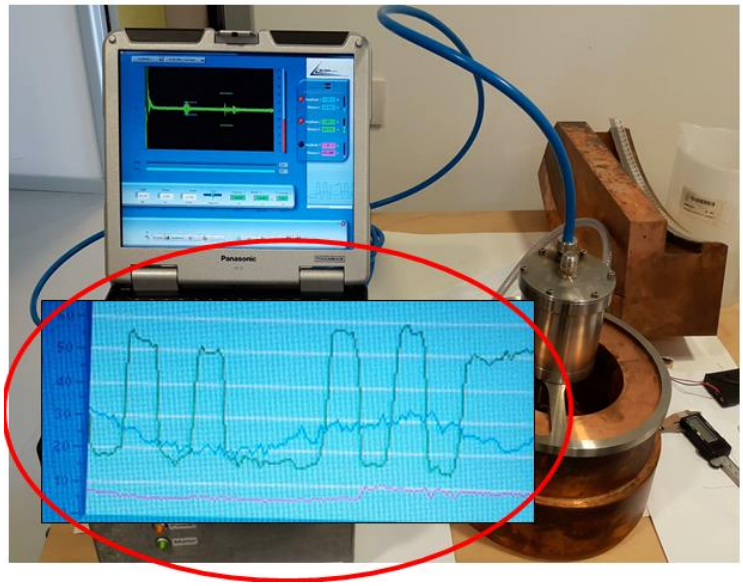

FIG. 5. Reading system prototype and binary code acquired by a 360˚ rotation of the transducer around the small scaled copper lid.

Chamfers should be designed to do not affect too much copper and maximize the ultrasonic echo received by the transducer. Depending on the chamfer inclination, in fact, the probe orientation should be adjusted in order to have always the perpendicularity between the reflective surface and the ultrasonic probe. The width of chamfer, instead, must be selected in order to do not alter the canister stability and then smaller they are, better it is. However, if too small, they could not be detected during the ultrasonic inspection and then a compromise must be found. For this purpose, several CIVA software simulations have been carried out considering a 10MHz frequency probe and chamfers 5, 10, 15 and 20 mm wide with inclinations 55˚ and 50˚. CIVA is a multiple-expertise software platform for Non Destructive testing (NDT) that includes different modules among which the Ultrasonic Testing (UT) module. Results of simulations revealed that wider is the chamfer, higher is the ultrasonic echo. However, a chamfer 10 mm wide and 55˚ inclined seems to be the best compromise between the need of having a good ultrasonic echo and do not change too much the canister geometry. In fact, the area to be removed, in case of chamfers with these features, is about 20 mm2, which corresponds to about 4.3 g of material. The impact of chamfers on canister structure is also related to the number of chamfers to be machined around the lid circumference and their angular extension.

There are different ways to realize unique codes arranging chamfers around the lid circumference. The first idea proposed by authors was to realize a binary code considering “1” in correspondence of a chamfer (detected ultrasonic echo) and “0” otherwise. However, the number of chamfers to be machined for the identification of about 6000 canisters would be around 14. Therefore, in order to do not change too much the lid geometry, the number of chamfers has been reduced elaborating another type of coding. The new solution involves the division of the lid circumference into four imaginary sections 27º wide representing thousands, hundreds, tens and units. Each section, in turn, is divided into nine slots of 3º which can host or not a chamfer. Depending on which slot of each section is occupied by the chamfer, it is possible to give a unique ID number to a canister. An example of this coding is illustrated in Fig. 6. All the chamfers to be machined are 3º angularly wide and there is a reference chamfer of 6º to represent a starting point for decoding. In this way, using a maximum of four chamfers plus the reference (which means removing only 26 g out of 708 kg of the copper lid), it should be possible to uniquely identify more than 6000 canisters.

This new coding solution has not been already physically implemented on a full-scale copper lid; however, CIVA simulations put in evidence the possibility to detect with a good signal to noise ratio chamfers 55º inclined, 10 mm wide and with an angular extension of 3º.

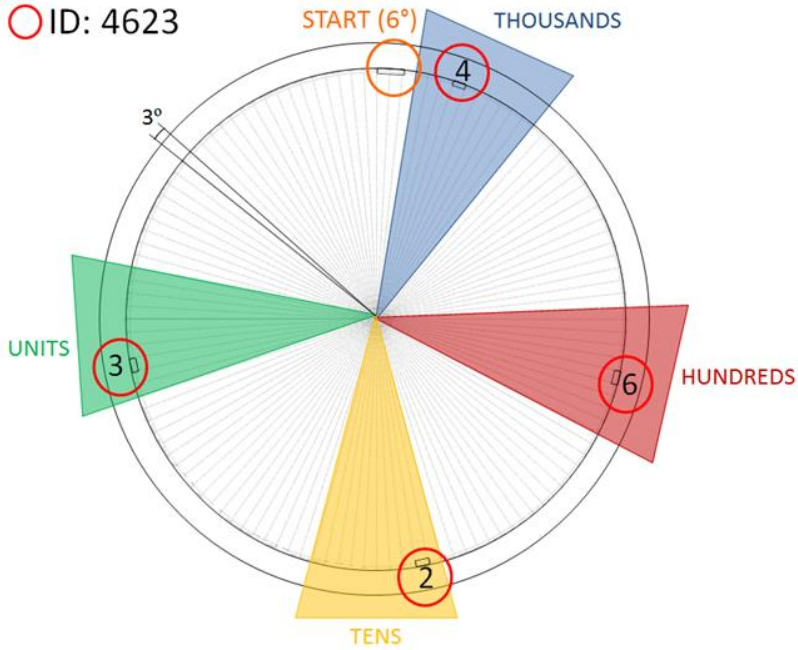

FIG. 6. Possible chamfers disposition to identify uniquely a copper canister (ID 4623).

2.2. The authentication

In addition to the identification fingerprint, an authentication signature should be realized in order to assess the authenticity of each canister. The idea proposed by the authors is based on the research of a natural fingerprint, intrinsically contained into copper canisters. In fact, after the encapsulation of the fuel, a lid is welded onto the canister by Friction Stir Welding (FSW). A rotating tool is plunged between the surfaces to be welded and makes the material plastic by the heat generated with the friction. During the tool movement the two pieces are stirred together and a joint is realized [11]. The weld joint design includes a gap between the lid and the tube. This gap represents a discontinuity in the material, detectable by an ultrasonic transducer (Fig.7). The extension of the gap, in fact, is about 0.3-0.6 mm and then an ultrasonic probe with a 10MHz of inspection frequency can detect it.

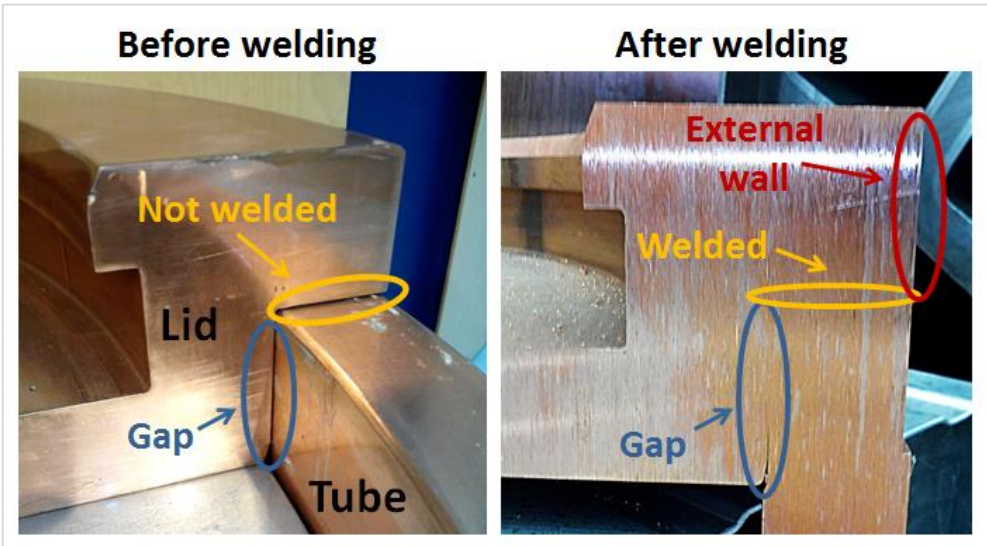

FIG. 7. On the left, copper lid and tube before welding. On the right, lid and tube welded. The internal gap between lid and tube is included in the weld joint design and then is detectable by ultrasound even after the welding process.

The welding area, including the internal gap, can be inspected by an ultrasonic probe placed as in Fig. 8. Depending on the height h of the transducer, the amplitude of the internal gap echo could be lower while the amplitude of the external wall echo could become higher. The variation of these echoes' amplitude is related to the material structure and copper grains dimension. Since the copper lid is forged and pressed before welding and final machining, its internal structure could be composed by grains with various dimensions that when investigated by ultrasound could attenuate the beam in different ways. In addition, the height of the gap around all the circumference of the lid can vary according to the welding process.

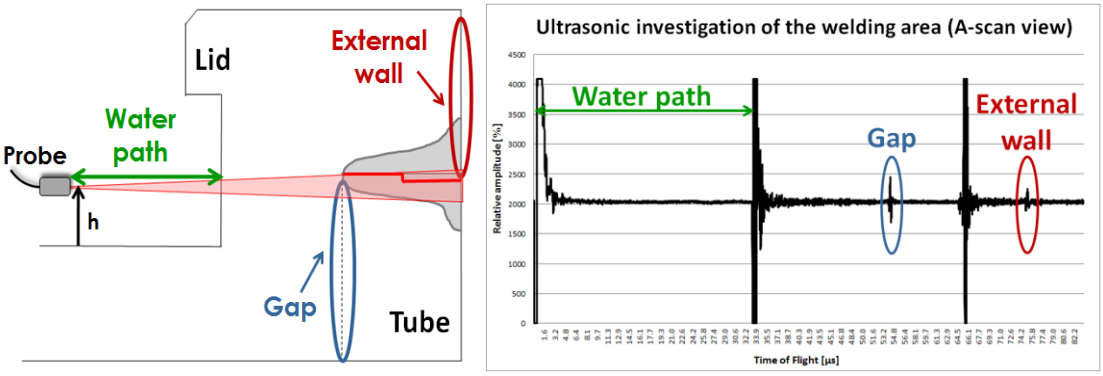

FIG. 8. Ultrasonic investigation of the welding area by an immersion testing. The correspondent A-scan acquisition is on the right. The echo of the internal gap (in blue) and the echo of the external wall (in red) are clearly detectable by the probe at fixed height h.

Therefore, rotating the transducer all around the canister circumference, it is possible to acquire an ultrasonic amplitude response of the gap or the external wall, which is strictly related to material properties and then could be an authentication fingerprint, different for each canister [12]. The uniqueness of this fingerprint is not already demonstrated but first experimental tests are carried out to investigate to what extent the variation of received signals is related to the canister structure, after the welding process.

The experimental validation of the authentication concept has been realized on two copper lids already welded onto tubes (FSWL121 and FSWL122) at the SKB's Canister Laboratory in Oskarshamn. The aim of these inspections was to verify the detectability of a fluctuating fingerprint and its repeatability. The device used to scan the two samples is developed by the SILab and is mainly composed by a reader, a control box and a computer (Fig. 9). 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. The probe is kept perpendicular to the lid surface and its distance can be adjusted from 50 mm to 25 mm, while height 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 computer displays the software interface for the setting of testing parameters and the signal processing.

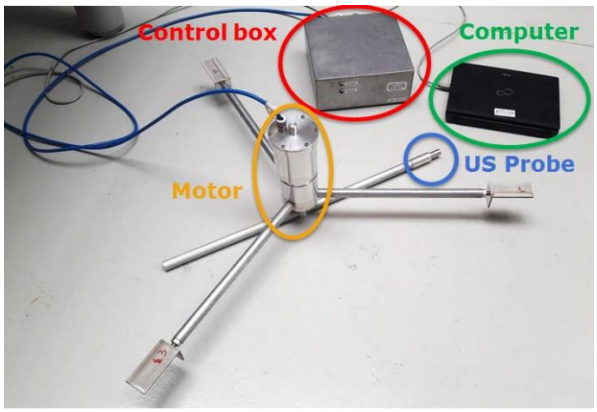

FIG. 9. Ultrasonic reader device used for inspections on copper samples.

In order to perform immersion tests, copper samples are placed in a tank with water and the reader is just places above the sample as shown in Fig. 10. Temperature variations during the ultrasonic test could affect the result of measurement. While in copper the variations of sound velocity due to temperature are negligible, the velocity of sound in water could fluctuate from 1403 m/s at 0°C up to a maximum of 1555 m/s at 74°C. However, the influence of temperature can be limited using a temperature sensor devoted to measure temperature variations during the ultrasonic testing. In this way, potential fluctuations in measurements could be compensated by a calibration algorithm based on the signals' adaptation on a unique scale.

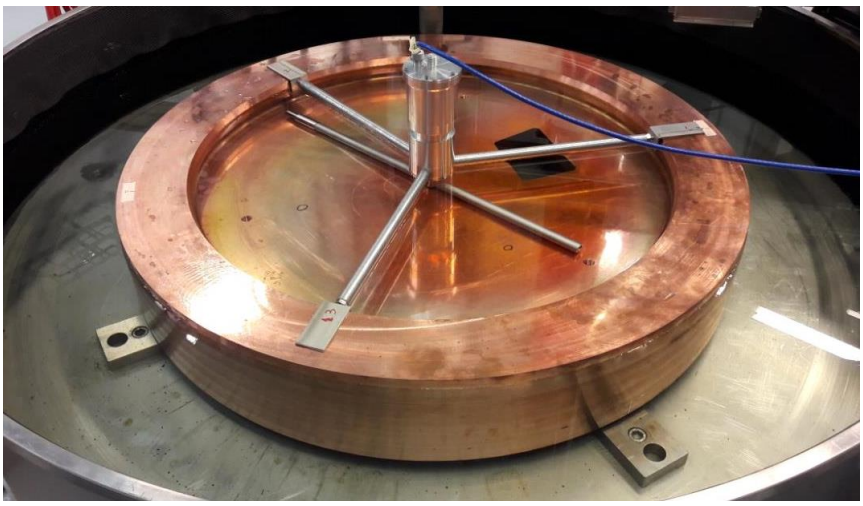

FIG. 10. Experimental testing of the IDA reader at the SKB's Canister Laboratory.

Several tests are carried out changing the height of the transducer and the position of the reader above the lid. Through the variation of the reader position, it is possible to verify the reader ability to perform repeatable measurements while, adjusting the probe height, it is easier to appreciate variations of the ultrasonic amplitude response in the entire welding area. Among all the acquired signals, the following picture (Fig. 11) shows the ultrasonic investigation of the lid at 19 mm of height. The curve in blue represents the amplitude response of the internal gap echo while the red signal is the amplitude response of the external wall echo. The presence of both echoes means that at that height the probe is able to acquire reflections from both surfaces. However, there is a part of the amplitude response of the gap which is practically zero (green area in the picture) and this is because the weld joint is perfect, and ultrasounds can penetrate in the material without reflection up to the last interface that is the external wall of the canister.

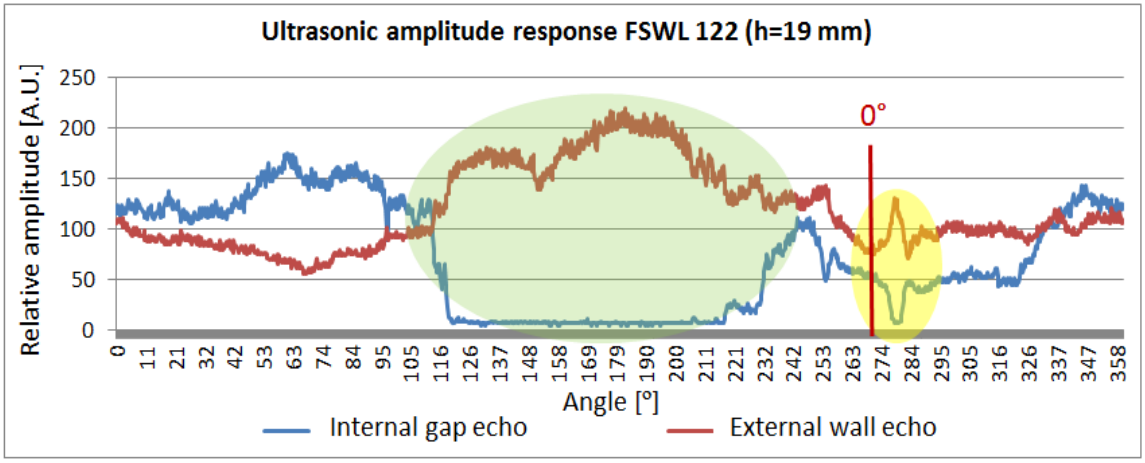

FIG. 11. Ultrasonic amplitude response of FSWL 122 at 19 mm height.

Another interesting part is highlighted in yellow in the picture. There is a signal inversion which corresponds to the point where the welding tool passes two times during the welding process. This statement is also in accordance with the position of the entry point (vertical red line in the picture) of the welding tool.

Following the analysis of echoes at different heights, we can observe that acquired amplitude responses are quite fluctuating and their content is related to material variations [13]. Consequently, the investigation of the welding area could be used as an authentication technique for copper canisters and further inspections should be realized to make evidence of differences between different containers.

2.3. The angular matching between fingerprints

In order to increase the robustness and reliability of the ultrasonic method, a combination between the identification and authentication fingerprint has been accomplished. In particular, the two fingerprints can be integrated by angular matching to generate a third signature, unique and more difficult to replicate (Fig. 12). As shown in Fig. 13 in fact, depending on how fingerprints are overlapped, the third signature could be different and then attempts of falsification or duplication can be detected.

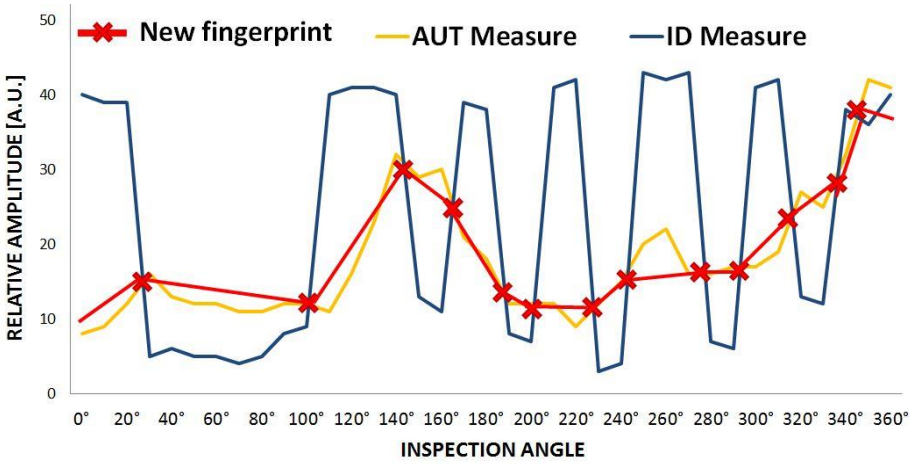

FIG. 12. The angular matching between identification (ID Measure in blue) and authentication (AUT measure in yellow) fingerprints creates a new fingerprint (red line) that is unique and robust against falsification.

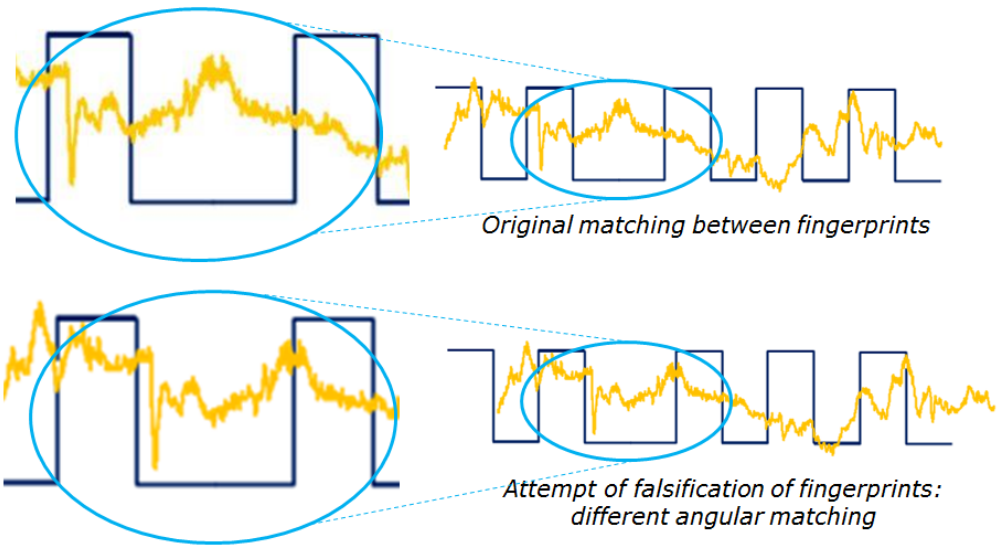

FIG. 13. Detection of a different fingerprint in case of a falsification attempt.

The acquisition of both fingerprints could be realized by a reading device (Fig. 14) consisting of a big cylinder that includes a water container for the immersion testing, the control electronics and two probes: the one for the detection of chamfers' code (identification fingerprint) and the other for the acquisition of the amplitude responses of the welding area (authentication fingerprint). By a 360º rotation of the whole structure, the two signatures are recorded and saved for the post processing. The angular matching between signals could be then implemented at the end of measurements.

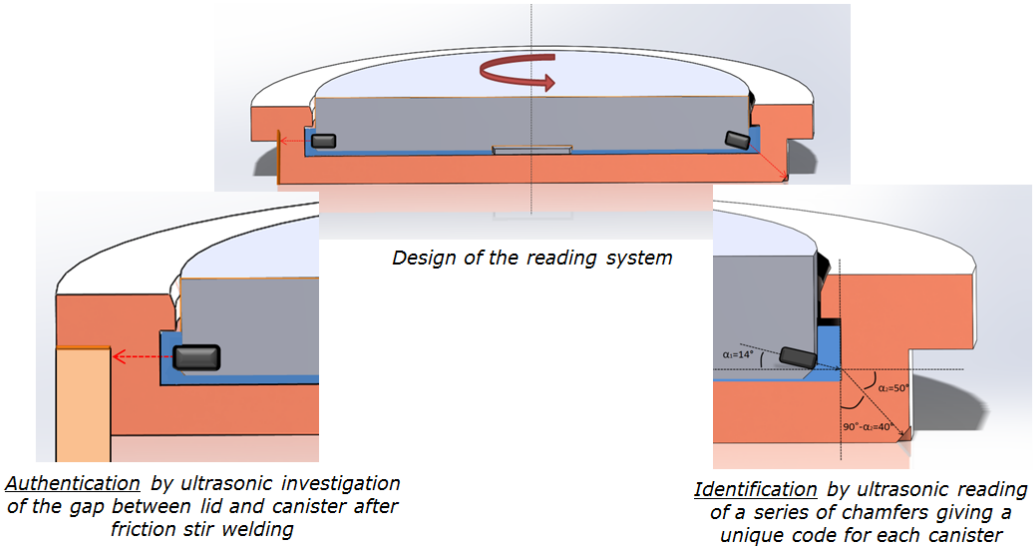

FIG. 14. Ultrasonic system for the acquisition of identification and authentication fingerprints on copper canisters for spent nuclear fuel.

The final reading system will be operated remotely and put in place by a crane or robotic arm and automatically centred on the lid. Once in place, water included in a tank will be released and poured on the external concave lid part, making an ideal and easy solution for the ultrasonic probe coupling. After a 360° inspection, the two curves are registered, stored or sent wirelessly to a control station. The first reading could be accomplished at the encapsulation plant to acquire a reference. In case of CoK losses, the system could be used to recover it. A portable version could be developed to make fingerprints verification whenever it is required.

3. CONCLUSIONS

Copper canister identification and authentication might be used to maintain CoK of nuclear spent fuel during encapsulation, transport and final disposal. Among different technologies, ultrasounds could be used for identifying uniquely canisters. The ultrasonic amplitude response related to the investigation of a configuration of chamfers arranged around the lid circumference could represent a unique fingerprint. According to first experimental tests and simulations, identification could be accomplished using configurations of chamfers which do not affect too much the canister structure. However, further studies should be performed to verify the robustness of the fingerprint over time.

In addition to the identification code realized by chamfers, the ultrasonic investigation of the welding area between the copper lid and tube could be used as a natural fingerprint to authenticate canisters. The Friction Stir Welding process provides a very high quality weld along the joint line but beneath it, according to the design of the canister, an internal gap remains. The ultrasonic investigation of this gap with high resolution probes, generates an amplitude response which is strictly related to the height of the gap and the material structure after forging and welding of the copper lid. The experimental tests on copper lids already welded performed at the SKB's Canister Laboratory in Oskarshamn put in evidence the possibility of acquisition of fluctuating fingerprints, strictly related to material properties. However, the uniqueness of the welding area should be verified with further tests on different samples.

In order to increase the robustness of the method, the angular matching between the two fingerprints has been introduced. In case of falsification attempts, a third fingerprint resulting from the overlapping of the

previous two can be used to verify the originality of the canister. The design of a potential reader has been described in the end.

In conclusion, the ultrasonic identification and authentication of copper canisters has been validated in laboratory and future researches should be carried out on full scale lids already welded with chamfers in order to assess the detectability of signatures.

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