Identification of copper canisters for spent nuclear fuel: the ultrasonic method

Chiara Clementi[1,2], **Lorenzo Capineri**[2], **François Littmann**[1]

[1] Nuclear Security Unit, Joint Research Centre, European Commission, Ispra (VA), Italy
[2] Dept. Information Engineering, University of Florence, Florence, Italy
E-mail: chiara.clementi@ec.europa.eu, francois.littmann@ec.europa.eu, lorenzo.capineri@unifi.it

Abstract:

The long-term storage of spent nuclear fuel in geological repositories has introduced the need to develop new safeguards procedures, measures and technologies. For the proposed Swedish disposal process, the Continuity of Knowledge (CoK) of fuel during transport from Oskarshamn and deposition of the same copper canisters at Forsmark is a challenging topic. Several Containment and Surveillance (C/S) measures could be used for this purpose; among them, the identification and authentication of copper canisters could be useful to trace canisters during transport. Ultrasonic techniques are used by authors to acquire unique fingerprints from each container. The ultrasonic amplitude response of a series of chamfers machined in the inner part of the copper lid can be used as a unique signature readable from outside the canister. In addition, canisters can be authenticated by investigating the welding area between the lid and the canister itself. The robustness of this approach is guaranteed by the angular matching between the identification and authentication fingerprints to produce a third unique fingerprint, more reliable than the other two. Several experimental tests are performed to validate the approach and optimize the design of a device for the acquisition of ultrasonic fingerprints. A potential implementation of this device within the Swedish disposal process is also studied. The acquisition of ultrasonic references could be carried out after canisters' final machining at the encapsulation plant and the process could be completely automated. The reduced cost of realization and its ease of use are the main advantages of the method. However, the machining of chamfers on copper lids requires the introduction of further steps in the manufacturing process of containers.

Keywords: ultrasound, identification, authentication, copper canisters.

1. Introduction

The final disposal of spent nuclear fuel in geological repositories introduces the need to revise safeguards approaches for a safe and secure handling of the fuel [1]. In 2011 the Swedish Nuclear Fuel and Waste Management Co. (SKB) submitted an application for the construction of a long-term geological repository in Forsmark (Sweden). The SKB method for final disposal is based on a multi-barrier system: copper canisters with iron inserts are used to host fuel assemblies; the bentonite clay is then used to cover canisters once deposited in tunnels and the bedrock isolates canisters from human-beings and the environment for thousands of years. The spent nuclear fuel coming from nuclear power plants will be stored for a period in pools at the Central Interim Storage Facility (Clab) in Oskarshamn. Then fuel assemblies will be dried and inserted in copper canisters with iron inserts at the encapsulation plant (that will be built next to the Clab). Canisters are big cylinders, about 5 m high and 1 m in diameter with a lid and a tube welded together by Friction Stir Welding (FSW). After the encapsulation of the fuel, copper canisters will be placed in transport casks and temporarily stored before being shipped to the final repository in Forsmark (Figure 1). At this facility, canisters will be reloaded to a deposition machine in the underground central area and then the canisters will be deposited in tunnels, later backfilled and sealed with a concrete plug. A total amount of 6,000 canisters will be deposited underground with an average of one canister per day, over roughly 40 years [2]. The International Atomic Energy Agency (IAEA) model integrated safeguards approach for geological repositories foresee that Containment and Surveillance (C/S) measures should be applied to guarantee Continuity of Knowledge (CoK) of spent nuclear fuel during storage and transport of copper canisters [3].

Clementi, C., Capineri, L., & Littmann, F. (2019). Identification of copper canisters for spent nuclear fuel: the ultrasonic method. *ESARDA Bulletin - The International Journal of Nuclear Safeguards and Non-proliferation*, 58, 55-62. https://doi.org/10.3011/ESARDA.IJNSNP.2019.7

Figure 1. The spent fuel transfers in the Swedish system for final disposal of spent nuclear fuel.

Since in Sweden the encapsulation plant and the geological repository are not located on the same site safeguards approaches defined by the IAEA should be adapted to ensure CoK throughout the handling chain of the copper canisters. Surveillance systems could be used inside facilities to monitor the flow of spent nuclear fuel, while seals applied on transport casks could guarantee the identity of canisters during the transport from the encapsulation plant to the geological repository. However, in case of failure of one of the two measures, the identification of copper canisters by a unique tag could be adopted to recover CoK. Tagging devices should give a unique identifier to each canister (identification fingerprint) and return evidence of falsification attempts (authentication fingerprint). External engraving of canisters should be avoided because it could trigger a corrosion process. Moreover, according to geometrical features, the minimum copper thickness to assure the stability of canisters' structure is 50 mm. The majority of conventional tagging devices used to identify uniquely nuclear items are analysed in [4] to see to what extent they could be adopted in the case of copper canisters. As a result, even if the identification of canisters could be realized with different methods, such as Reflective Particle Tags (RPT), ultrasonic methods or Tungsten-based Identifiers, the verification of authenticity is complex since it should be accomplished by techniques which analyse intrinsic properties of a canister. The ultrasonic method seems to be the only one able to identify and authenticate copper canisters. A description of this method for copper canisters identification and authentication is reported in the paper, discussing advantages and disadvantages for a potential implementation in the Swedish system for final disposal.

2. The ultrasonic method

Ultrasound constitutes pressure-waves which can propagate across a specimen and are reflected whenever a discontinuity is encountered, i.e. a boundary between means of different acoustic impedances. At the interface between air and copper, for example, since the acoustic impedance mismatch is large, a couplant, such as water, is necessary to allow the transmission of the ultrasonic beam in copper. Canisters for spent nuclear fuel are made of copper to provide safety during handling and emplacement of the fuel in the repository and also to ensure isolation from the biosphere for thousands of years. Ultrasonic non-destructive testing is used to check the integrity of copper canisters and also the quality of the weld between lid and tube after the encapsulation of the fuel. However, the investigation of canisters by ultrasound could also be adopted for the acquisition of a unique identifier from each container. Ultrasonic techniques for reading bolt seals with artificial cavities applied on nuclear casks deposited in underwater and dry storages have been used in the nuclear field for twenty years. In the case of copper canisters for spent nuclear fuel, the ultrasonic method for the identification and authentication of each container is based on the acquisition of two fingerprints by ultrasound.

The identification signature is created by machining a series of chamfers machined in the inner surface of the canister's lid where the copper thickness is greater than 50 mm. Chamfers are arranged around the lid circumference creating a unique code for each canister, readable by rotating a transducer as placed in Figure 2. The ultrasonic probe is kept inclined, in order to maintain the probe perpendicular to chamfer surfaces to obtain reflections according to Snell's law. Whenever a chamfer is detected, an echo is received by the probe and values of amplitude and time of flight are collected. By a 360° rotation of the probe around the lid circumference, a unique code, strictly related to chamfers' position, can be acquired. In particular, the ultrasonic amplitude response of the chamfers represents an identification fingerprint for each copper canister. Acquiring this signature can be accomplished by immersion testing with water and the probe could be rotated automatically with a motor remotely controlled.

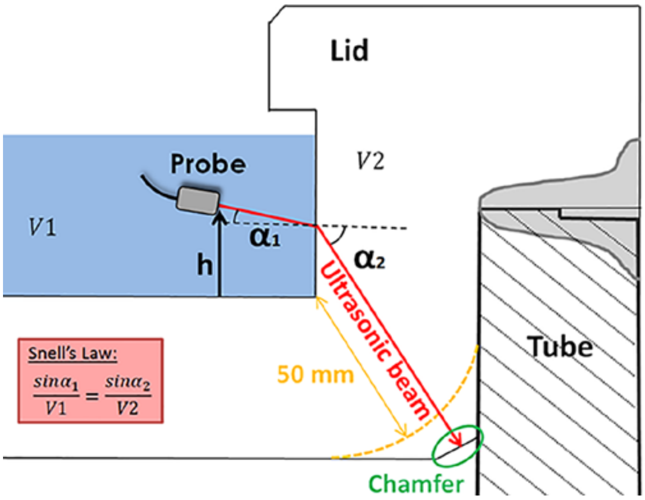

Figure 2: Ultrasonic investigation of chamfer (circled in green) machined in the inner part of the copper canisters' lid. V1 and V2 are the velocities of sound in water and copper respectively while α_1 and α_2 are the angles of incidence and transmission of the ultrasonic beam (red arrow).

The geometry of chamfers should be defined, on the one hand, to maximize the signal-to-noise ratio of the ultrasonic investigation and, on the other, to not affect the copper canisters' geometry too much. For this purpose, simulations and experimental tests on a laboratory mock-up have been carried out. As reported in [5] the acquisition of chamfers' amplitude response was carried out on a ¼ scaled version of the copper lid with chamfers arranged around the circumference. The immersion test with an inclined probe, rotating 360° around the mock-up, confirmed the possibility of acquisition of an ultrasonic amplitude echo, whose variation is correlated to chamfers position.

Afterwards, results of simulations with CIVA software [6], revealed that the best compromise to meet all the requirements is a 10 mm wide chamfer with an inclination of 55°. This solution involves removing only 4.3 g of copper out of the full-sized 708 kg lid. Moreover, this chamfer length will ensure a good signal-to-noise ratio in the ultrasonic inspection also when varying the probe inclination, and in case of temperature variations in the water used for the immersion test. Temperature changes, in fact, affect the velocity of sound in medium and as a result, the ultrasonic investigation itself. While in copper these variations are negligible, in water the velocity of sound fluctuates from 1403 m/s at 0°C up to a maximum of 1555 m/s at 74°C with a percent variation of about 11% [7]. According to the Swedish design criteria, the maximum temperature of the canisters' outer surface is around 100°C. The CIVA simulations show that 10 mm wide chamfers can be clearly distinguished from the rest of the lid even in varying temperatures as shown in Figure 3. The echo amplitude of the chamfer 10 mm wide (green curve) is higher than without chamfers (blue curve). Therefore, in a range of temperatures between 5°C and 100°C, a chamfer 10 mm wide can be detected with a good margin: as shown in Figure 3 the amplitude acceptance threshold at 0.04 (red line) is 10 times bigger than the maximum amplitude without chamfers. In case of inspection with water temperatures below 7°C, chamfers can be discriminated as well, but the signal-to-noise ratio is lower than in the case of inspections with higher water temperature.

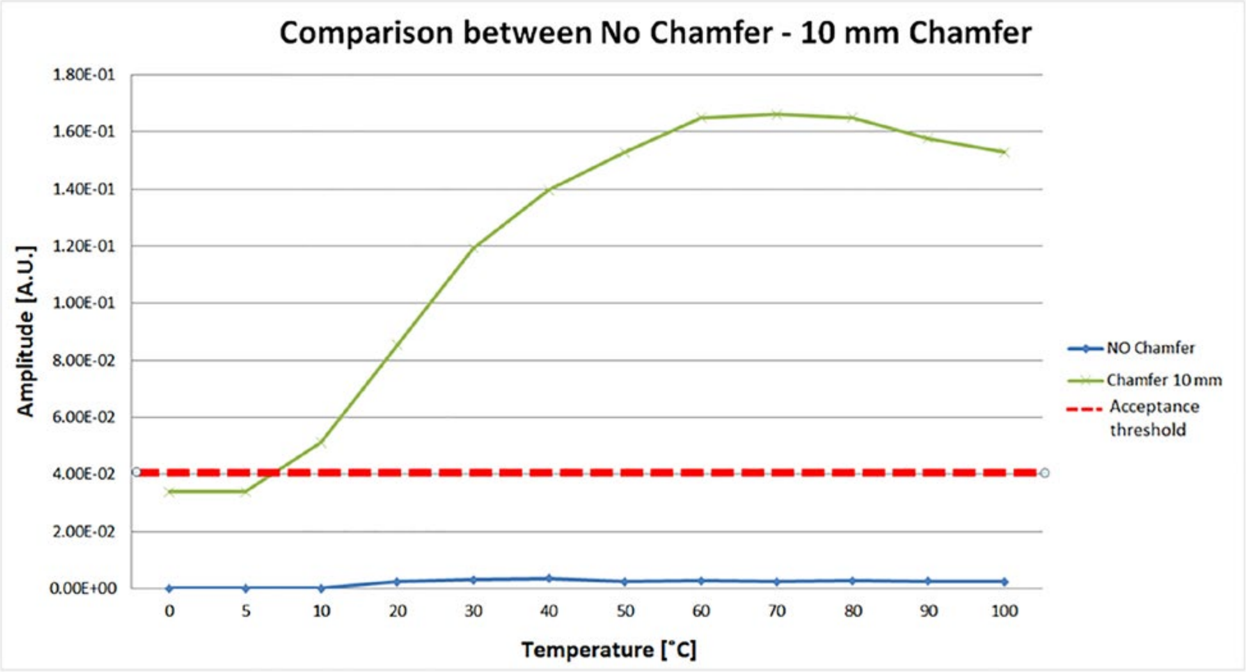

Figure 3: Simulation of the ultrasonic amplitude response acquired by the investigation of lid with (green curve) and without (blue curve) a chamfer 10 mm wide, considering a temperature variation from 0°C to 100°C. The red curve represents the acceptance threshold above which a chamfer 10 mm wide is well discriminated from the case with no chamfer.

The angular extension of chamfers is another important parameter which can impact on canister's geometry. The unique reflection realized by chamfers arranged around the lid circumference should be optimized in order to reduce the amount of copper to be removed. As a consequence, the early idea of a binary code with at least 13 chamfers and a reference for the identification of about 6,000 containers has been replaced with another coding. The new solution (Figure 4) splits the lid circumference into four imaginary sections 27° wide representing thousands, hundreds, tens and units. Each division is in turn divided into nine slots, which may or may not host a chamfer inclined 55°, 10 mm wide and with an angular extension of 3°. In this way, depending on which slot of each section is occupied by the chamfer, it is possible to give a unique ID number to a canister with only four chamfers plus the reference.

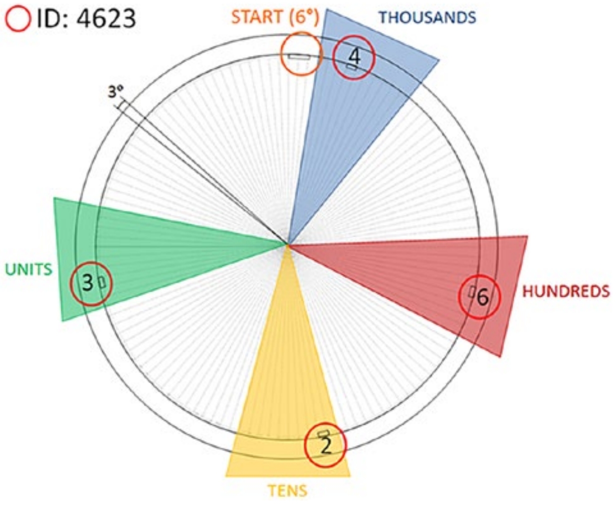

Figure 4: Proposed coding for chamfers to uniquely identify a copper canister (ID 4623).

To conclude, the identification of canisters is could be realized by chamfers machined on the lids inner surface, readable from outside by an ultrasonic probe. Nevertheless, the code created by chamfers could be duplicated and then another solution should be implemented to verify attempts of falsification. For this purpose, taking advantage of the ultrasonic transducer already implemented in the identification concept, a method to verify the canister's authenticity is developed.

In contrast to the identification fingerprint, the authentication signature is an intrinsic property of each copper canister. After the fuel assemblies have been encapsulated, the copper lid is welded onto the tube by Friction Stir Welding (FSW). A rotating tool penetrates between the two surfaces, heats the material and creates a joint [8]. According to the geometry design, two faces of the lid lean against the tube: at the end of the welding process, only one of them is welded to the tube and the other represents a gap between the lid and the tube. This discontinuity can be detected by an ultrasonic transducer as placed in Figure 5.

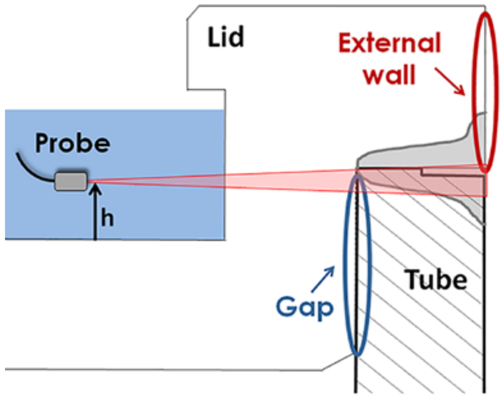

Figure 5: Ultrasonic investigation of the welding area between lid and tube of a copper canister. The probe is kept at a fixed height "h".

The ultrasonic amplitude response changes according to the variations of the gap height all around the lid circumference. Preliminary studies on copper flanges, i.e. slices of a copper lid already welded onto the tube, demonstrates the feasibility of the method: ultrasonic echoes from the internal gap and external wall surfaces have been acquired with a good signal-to-noise ratio using a 10 MHz immersion transducer [9]. Afterwards, experimental tests are carried out on full scale welded lids at the SKB's Canister Laboratory in Oskarshamn (Sweden). For this purpose, an ad hoc acquisition system prototype was designed. The reader, i.e. the device used to read authentication fingerprints, is made up by three steel arms, a motor devoted to the probe movement and a rotating bar to keep the transducer perpendicular to surfaces to be investigated. Signals are transmitted and received by an electronic module which is connected to another board for the control of the motor and power supply. Results of investigations are then processed and displayed on a computer [10]. The set-up of measurements for the investigation of welded copper lid is shown in Figure 6. Several measurements have been carried out, changing the position of the reader above the lid and the probe height in order to verify the repeatability of measurements and inspect a wide area of the welded region. Two time windows are used to acquire the maximum amplitude echo between the internal gap and the external wall.

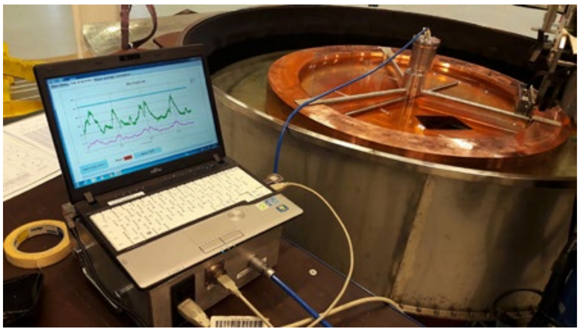

Figure 6: Set-up of measurements on copper samples: the reader for the scanning of the welding area is centred on the lid and signals are transmitted/received to/from the ultrasonic transducer by a control box connected to a computer for the processing and display of acquisitions.

After a complete rotation of the probe, the ultrasonic amplitude responses are collected and analysed. In Figure 7 is a display of the ultrasonic amplitude response of the internal gap (in blue) and the external wall (in red) on rotation angle of the probe. The two curves are quite fluctuating and present interesting peculiarities which can be unique to each container. However, the uniqueness of the welding area should be verified undertaking a statistical analysis of a consistent number of samples.

The ultrasonic method is based on the acquisition of ultrasonic-amplitude responses of chamfers (identification) and welded regions (authentication). While the first can discriminate each canister from another, the second helps to verify the authenticity of each canister. However, duplication of both fingerprints could make it difficult to ascertain the authenticity of a given canister. Therefore, we introduce a third fingerprint to our method to increase the reliability. The new fingerprint is simply realized connecting the intersection points between identification and authentication fingerprints. In this way, as shown in Figure 8, if the angular matching between the two fingerprints (blue line for the identification and yellow line for the authentication) is not the same as in the reference, it is possible to detect anomalies and demonstrate potential counterfeit canisters. A patent has been filed for both the identification and authentication approaches [11].

3. Potential implementation in the Swedish system

The adoption of the ultrasonic system could be extremely important in the case of failures of the other two main C/S measures: the monitoring devices and seals applied on transport casks. The encapsulation plant and the geological repository could be considered as black boxes where additional C/S measures are not necessary. However, during transport of copper canisters between the two sites, the use of dual C/S measures is recommended. Therefore, the implementation of an additional system to identify and uniquely authenticate each canister could be considered as a useful way to recover CoK in case of losses and not as a routine measure. The introduction of a unique identifier should also be combined with other techniques to verify the integrity of the canister and the fuel inside. This section describes how the ultrasonic method could be included within the Swedish system for final disposal.

The identification and authentication fingerprints, to be used as references, could be acquired at the encapsulation plant, stored in a database and then verified with other measured fingerprints, only in case of necessity. In general, performing verification measurements to assess the fuel and the canisters' integrity at the geological repository is not desirable, but since this should not be a periodic procedure, it could be useful to recover CoK using ultrasonic methods in case of the failure of other C/S measures. Ultrasonic fingerprints could be acquired at the encapsulation plant and a reference could be stored for each container. At the geological repository, these fingerprints could be verified in case of necessity and acquired responses could then be compared with references. At the encapsulation plant, after the encapsulation of the fuel, canisters are welded and ultrasonic and radiographic tests are then performed on each container to verify the quality of the weld. At this stage, reference fingerprints could be acquired. In particular, an ad hoc system could be developed to acquire automatically a reference signature from each

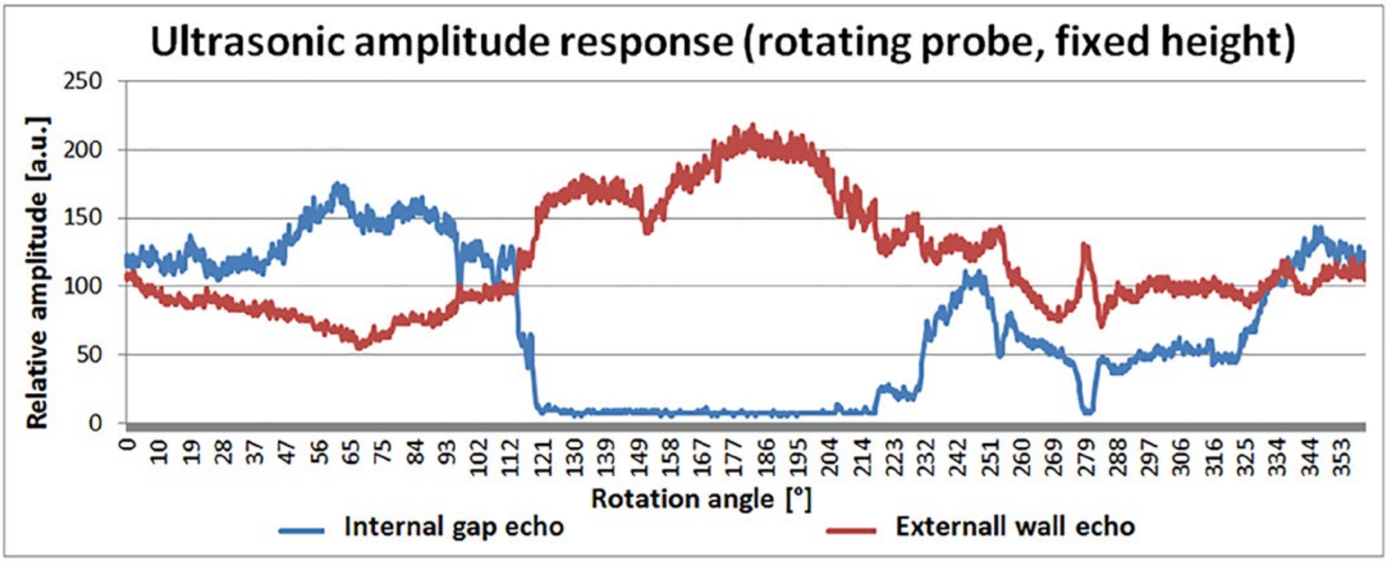

Figure 7: Ultrasonic amplitude response acquired rotating the transducer around the copper sample circumference with fixed height h. The red line is the amplitude response of the external wall while the blue line is the amplitude response of the internal gap.

canister. Ultrasonic measurements could be performed in the same room as the radiographic inspection of welds. A section view of the possible ultrasonic reader placed above a canister is shown in Figure 9. The device can be seen as an optimized version of prototypes already developed for laboratory tests. This new system includes a cylindrical box which hosts a tank for water, plus a motor and a rotating bar which supports two transducers (highlighted in yellow in Figure 9). One transducer is kept perpendicular to the welding area to acquire the authentication fingerprint and the other transducer is inclined according to Snell's law to receive echoes and furthermore to generate the identification code produced by the chamfers. The speed of the motor can be adjusted to optimize the acquisition of

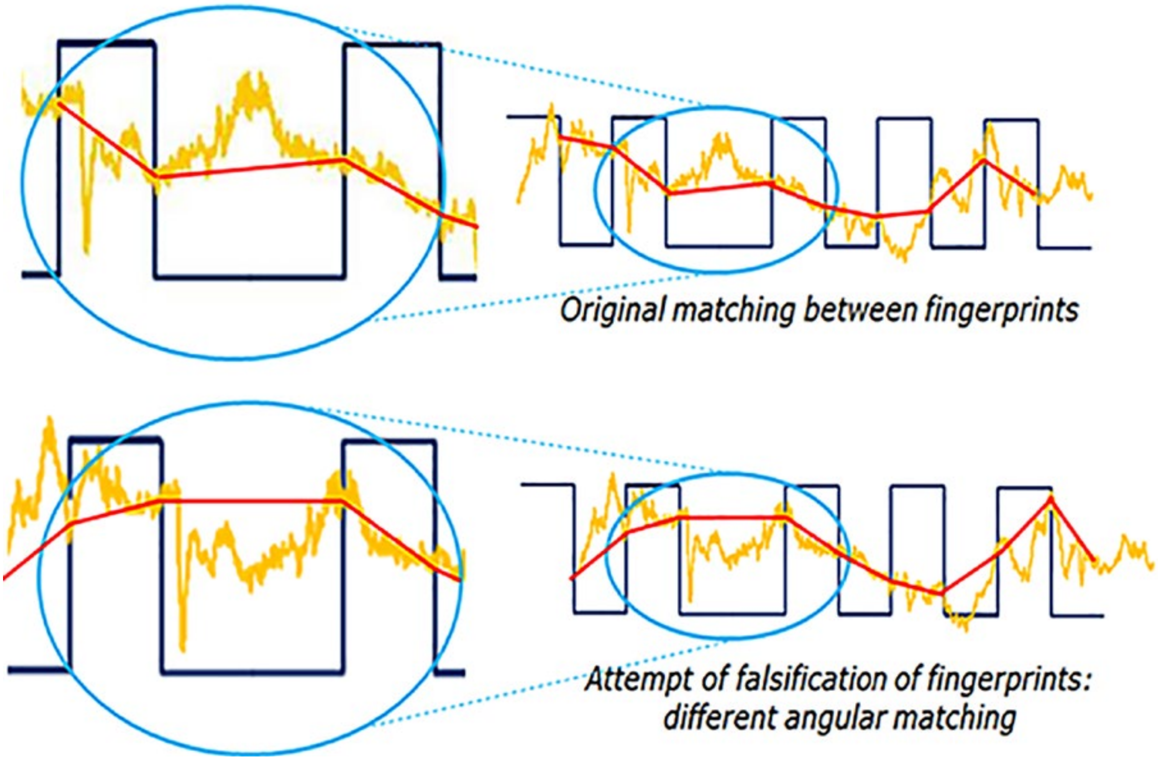

Figure 8: Comparison between a real fingerprint and a copy: the differences in angular matching between the identification (blue curve) and authentication (yellow curve) fingerprints can be detected analysing the trend of the third fingerprint (in red).

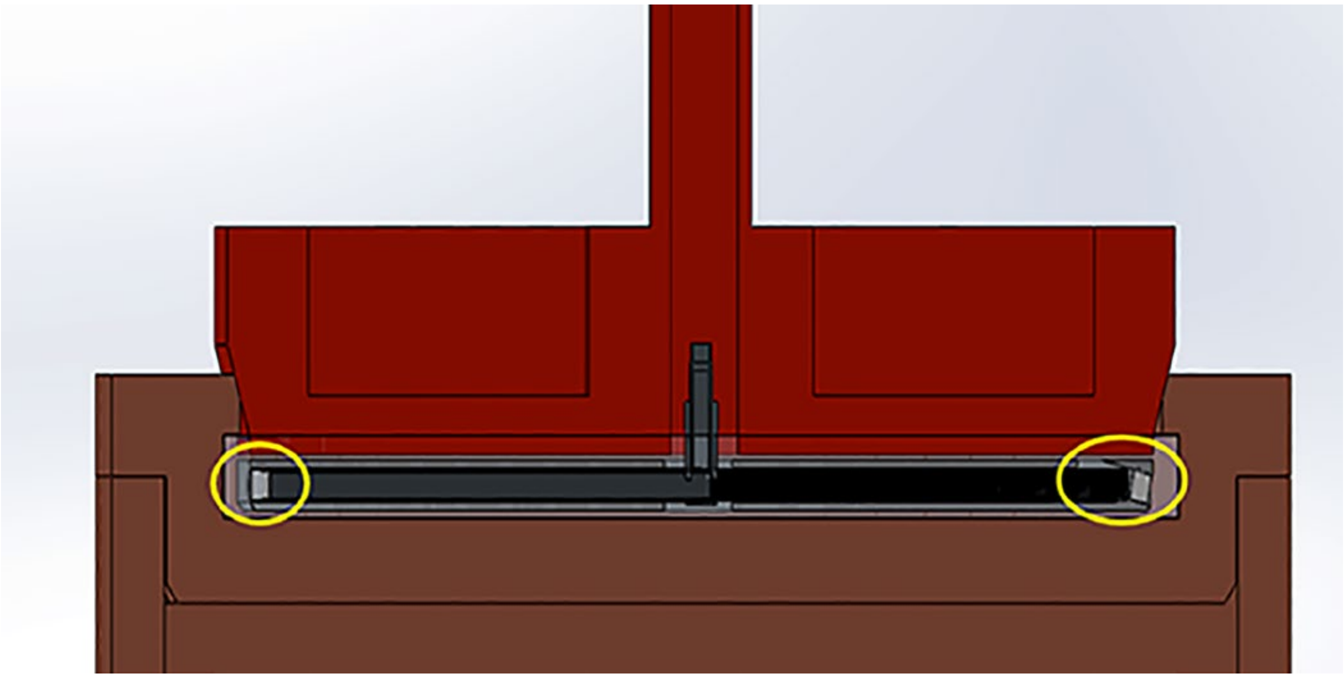

Figure 9: Section view of a CAD design of the ultrasonic reader device placed above a canister. Two probes (highlighted in yellow) rotate around the lid circumference to acquire the identification and the authentication fingerprints.

signals and different inspections can be performed changing the transducer height for the collection of a larger amount of data.

All ultrasonic measurements could be accomplished without the involvement of an operator: the reader system could be put in place by a crane or robotic arm and automatically centred on the lid (Figure 10). Once in place, water can be poured on the external concave of the lid and the ultrasonic immersion testing could be launched. After a complete rotation of both probes, the two curves are registered, stored in a memory card and sent wirelessly to a control station. The processing of signals for the definition of the third fingerprint can be done at the post-processing of data. At the end of the inspection, water will be pumped away from the lid.

All the electronics useful for the control of the motor and the transmission/reception of signals could be developed in an embedded version to fit inside a cabinet which could be placed in the same room as the measurements set-up (far from radiation emitted by the spent fuel inside the canister). All the reading processes could be monitored by surveillance devices and a complete rotation of transducers could be completed in a few minutes. Differently from other identification methods, the ultrasonic method is easy to implement and use, since it works automatically without the need of operators. In addition the cost of signatures' manufacturing is practically included in the canisters production costs. However, the realization of unique configurations of chamfers around copper lids involves the introduction of an additional step within the manufacturing process of canisters.

In the case of verification of fingerprints at the geological repository, a portable version of the same reader could be developed to make an easy verification whenever it is required.

A State might require that canisters be retrieved from a repository as a safety measure [12], as is the case for Sweden. Safeguards approaches have not been pre-determined for any retrieval scenarios. However, having a unique reference for each container could be useful to keep the CoK in case of retrieval, based on the hypothesis that the identification and authentication fingerprints would not be altered at that time, and there is knowledge available to use the ultrasonic methods for the identification of the canisters.

4. Conclusions

The final disposal of spent nuclear fuel introduces new challenges in the field of nuclear safeguards. The transport of copper canisters with spent nuclear fuel from the encapsulation plant to the final repository, as planned in Sweden, requires the implementation of supplementary C/S measures, in addition to dual surveillance and sealing systems, to be used in case of CoK losses. The ultrasonic method for the identification and authentication of copper canister is a potential way to help the recovering of CoK if necessary. However, canister identification should be combined with other techniques to verify the fuel integrity in order to recover the CoK. This method is based on the ultrasonic acquisition of two fingerprints. The ultrasonic amplitude response of a series of chamfers machined around the lid's inner surface could be used to generate an identification fingerprint. In addition, the ultrasonic amplitude response of the welding area between the copper lid and the canister can be used as an intrinsic fingerprint which authenticates each container since the ultrasonic amplitude response is only related to material properties and the welding process. Experimental tests were performed to validate both concepts and our results confirmed expectations. We recommend that future tests be performed on a full-scale copper lid with chamfers already

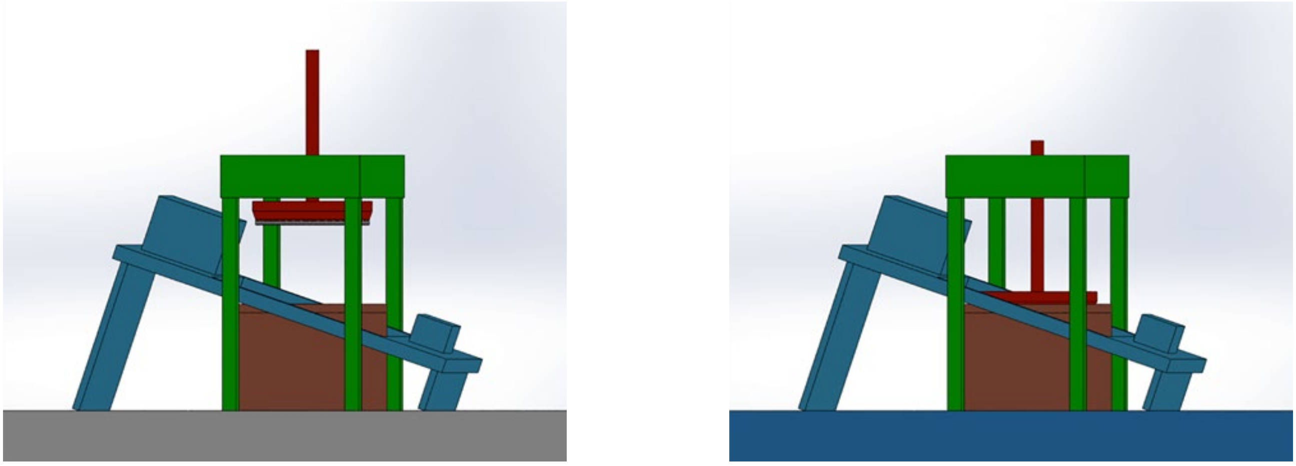

Figure 10: The ultrasonic acquisition of identification and authentication fingerprints could be performed in correspondence of the radiographic station for weld verification (in blue). On the left, the ultrasonic reader (in red) is lifted above the copper canister. On the right, a crane (in green) arranges the device on the canister.

welded to a canister tube in order to validate the third fingerprint described in Section 3. In fact, the angular matching between the identification and authentication signals could realize a third unique signature, increasing the robustness and reliability of the whole method. The design of an ultrasonic reader has been presented and its use has been optimized to avoid the involvement of an operator during the acquisition of fingerprints. The proposed version could be adopted within the encapsulation plant but a second version could be developed for the geological repository, by adapting of the one designed for the encapsulation plant.

5. Acknowledgements

This research has been accomplished by the Seals and Identification Lab (SILab) of the Joint Research Centre of the European Commission in Ispra in collaboration with the Department of Information engineering of the University of Florence. We would like to thank our colleagues from SKB for the copper samples provided to us for tests and all the expertise shared with us.

6. References

[1] af Ekenstam G.; Hildingsson L.; Fagerholm R.; Andersson C.; *Elements of a Swedish Safeguards Policy for a Spent Fuel Disposal System;* ESARDA Bulletin 54; June 2018; pp.36-41.

[2] Hildingsson L.; Andersson C.; Fagerholm R.; *Safeguards Aspects Regarding a Geological Repository in Sweden*; IAEA Safeguards Symposium, Paper CN-220-166; Swedish Radiation Safety Authority: Stockholm; Sweden; 2014.

[3] International Atomic Energy Agency: IAEA; *Model Integrated Safeguards Approach for a Spent Fuel Encapsulation Plant*; SG-PR-1305; ver. 1; 10 June 2010.

[4] Clementi C.; Littmann F.; Capineri L.; *Comparison of Tagging Technologies for Safeguards of Copper Canisters for Nuclear Spent Fuel*; Sensors 2018 18(4) 929; March 2018. Available online (accessed on Sept 28 2018): https://doi.org/10.3390/s18040929.

[5] Clementi C.; Littmann F.; Capineri L.; Andersson C.; Ronneteg U.; *Ultrasonic Identification Methods of Copper Canisters for Final Geological Repository*; ESARDA Bull. N.54; 2017, pp. 75–81.

[6] Ultrasonic Testing with Civa- Extende. Available online (accessed on April 15 2019): http://www.extende.com/ultrasonic-testing-with-civa.

[7] Engineering ToolBox, *Speed of Sound in Water*, 2004. Available online (accessed on Nov 10, 2017): https://www.engineeringtoolbox.com/sound-speed-water-d_598.html.

[8] Stepinski T.; Engholm M.; Olofsson T.; *Inspection of copper canisters for spent nuclear fuel by means of ultrasound Copper characterization*, *FSW monitoring with acoustic emission and ultrasonic imagin*; Uppsala University; Signals and Systems Department of Technical Sciences; Sweden; August 2009.

[9] Clementi C.; Capineri L.; Littmann F.; *Innovative Method to Authenticate Copper Canisters Used for Spent Nuclear Fuel Based on the Ultrasonic Investigation of the Friction Stir Weld*; IEEE Access 2017; Vol. 5; doi:10.1109/ACCESS.2017.2694878.

[10] Clementi C Littmann F.; Capineri L.; *Ultrasonic Investigation of the Welding Area of Copper Canisters for Spent Nuclear Fuel*; ESARDA Bull. N.56; 2018; pp. 19-27.

[11] Littmann F.; *Ultrasonic identification and authentication of containers for hazardous materials*; EP 16166465; April 21; 2016.

[12] Mongello R; Finch R. J.; Baldwin G.; *Safeguards Approaches for Geological Repositories: Status and Gap Analysis*. Available online (accessed on Feb 02 2019): https://www.researchgate.net/publication/280655578_Safeguards_Approaches_for_Geological_Repositories_Status_and_Gap_Analysis.