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ULTRASONIC PULSE-ECHO SYSTEM FOR MEASURING THE INTER-PLATE DISTANCE OF AN IRRADIATED FUEL ELEMENT

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ABSTRACT

The High Flux Reactor at the Laue Langevin Institute produces the most intense neutron flux in the world, with a thermal power of 58 MW. As part of the global non-proliferation initiative, the Laue Langevin Institute aims to convert highly enriched fuel into low enriched uranium. This conversion is a challenging process, requiring strict compliance with safety standards and the preservation of the same performance quality for the new fuel element. During an irradiation cycle of the fuel element, multiple microstructural and physicochemical transformations occur, depending on the specific irradiation history of the fuel element, leading to a swelling phenomenon of the fuel plates and a decrease in the inter-plate distance. The Perseus project therefore aims to develop new evaluation tools, particularly a measurement of the inter-plate distance using an ultrasonic pulse-echo system with a frequency of 100 MHz. In this article, we will present the system developed over the course of three theses, the different solutions implemented to measure the inter-plate distance on an irradiated fuel element. The radiation-resistant transducer, custom-built along with its instrumentation, and the associated signal processing will be detailed to present measurements on irradiated fuel elements.

Keywords: *ultrasonic sensors, distance measurement, high-flux reactor.*

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1. INTRODUCTION

The High-Flux Reactor (RHF) at the Institute Laue Langevin (ILL) generates the world's most intense neutron flux with a thermal power of about 58 MW [1-2]. As part of a global nonproliferation initiative, ILL aims to convert the RHF from high enriched uranium to low enriched uranium, a challenging process that must maintain safety standards and performance quality [3-5].

High Performance Research Reactors (HPRR) produce neutrons for material testing or science through fission in the reactor's fuel. During an irradiation cycle, various micro-structural and physical-chemical transformations occur in the fuel element. Post-irradiation examinations are essential to assess new fuel elements, identify structural modifications, and control irradiation histories [6]. Post-irradiation examinations activities, conducted in highly radioactive environments, require specialized infrastructure such as visual examination, radiography, and ultrasonic testing. Ultrasonic measurements are particularly valuable for nondestructive evaluation in the nuclear industry [7-10].

The Institut Laue Langevin and the University of Montpellier's Institute of Electronics and Systems launched the PERSEUS project to estimate the inter-plate distance within an ILL HPRR spent fuel element, linked to the RHF irradiation history. An ultrasonic device with a double element transducer was engineered and tested in the lab for in-situ measurements [11]. A mechanical system was developed to control the device underwater during testing. The paper discusses experimental constraints, the ultrasonic device and mechanical holder's structure and behavior, the instrumentation, and the time of flight estimation process. Section 4 covers in-laboratory measurement and calibration, and Section 5 presents the main result: an in-situ estimation of the water-channel profile along 50 cm. The paper concludes with future perspectives.

2. EXPERIMENTAL CONSTRAINTS

To evaluate the irradiation history of the ILL RHF fuel element, several experimental constraints must be considered. First, non-destructive post-irradiation examinations are necessary to ensure the integrity of the fuel element. High precision measurements are required despite the challenging access to the element, which is submerged in a moderating water pool at a depth of 12 meters for cooling after use. Additionally, the fuel plates have involute shapes to maintain a constant nominal inter-plate distance of 1.8 mm, limiting the ultrasonic device's thickness to 1 mm. The desired measurements need micrometric resolution to detect expected microscopic structural modifications of around 25 µm, necessitating high-frequency operation to achieve resolutions of about 1 µm. The ultrasonic device must be carefully designed, as the wavelengths are comparable to its microstructure, significantly affecting the device's ultrasonic response. Finally, since the measurements are conducted in a highly radioactive environment, special attention must be given to the materials used in the ultrasonic device to ensure its performance when introduced into a spent fuel element. The following section details how we addressed these constraints through the design of the ultrasonic device and its integration into a measurement system.

3. EXPERIMENTAL SETUP

3.1 Measurement principle

Nondestructive testing has become crucial in the nuclear industry for assessing the efficiency and safety of nuclear power generation, especially in complex geometries like the High-Flux Reactor (RHF) at the Laue Langevin Institute [12]. Previous research led to the development of a measurement system to estimate the RHF fuel element's water-channel thickness (Fig. 1) [11-15]. This system, requiring expertise in electronics, high-frequency acoustics, and mechanics, has now been optimized to measure the inter-plate distance, known as the water-channel thickness.
The measurement system uses a waterproof dual piezoelectric transducer, which acts as both an emitter and receiver, integrated at the end of a 1 mm steel blade. When the blade is inserted into the nominal 1.8 mm inter-plate distance, (Fig. 2) the transducers are connected to a pulser/receiver to transmit and receive ultrasonic waves. These waves undergo specific signal processing to evaluate the inter-plate distance.

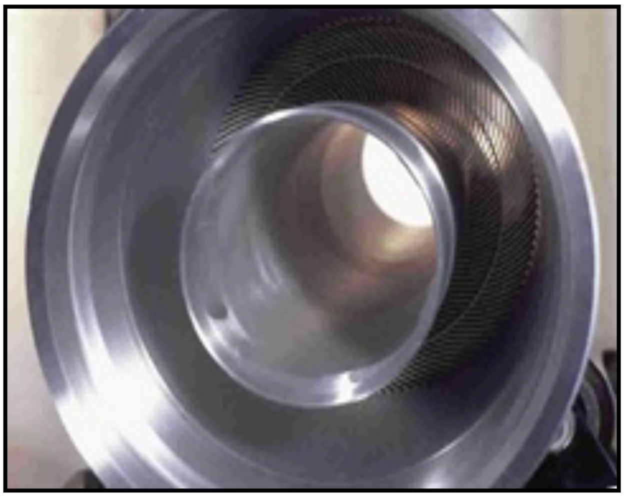

Figure 1. Bottom view of an RHF fuel element.

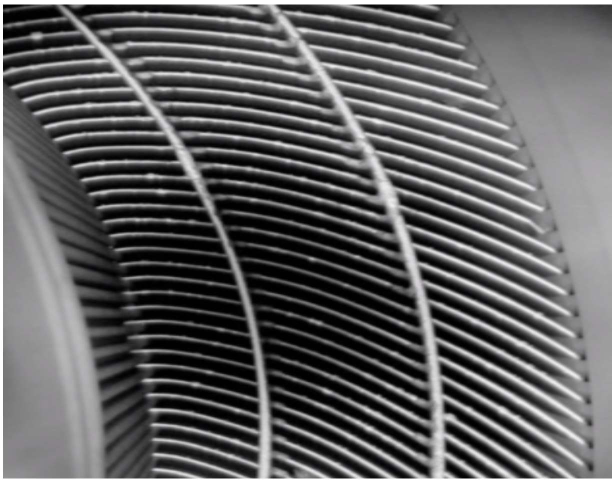

Figure 2. Enlarged top view of the plates of a fuel element with the channels whose distance needs to be measured.

The measurement principle involves two piezoelectric elements bonded to both faces of a silica support, mounted on one end of a 1 mm thick, 10 mm wide, and 1500 mm long stainless-steel blade (Fig. 3). After the blade is introduced into the water channel, the inter-plate distance is measured using ultrasonic waves emitted and received by a dual transmitter/receiver system. The pulse echo method quantifies the time of flight t between reflections on the silica support and the fuel plates. Based on the ultrasonic velocity c in the propagation medium, the distance d is calculated using the formula in Eqn. (1).

$$d = (c*t) / 2. \qquad (1)$$

By summing the distances d_1 and d_2 and adding the thickness d_s of the silica (Fig. 3), the measurement of the water channel thickness d_{wc} can be calculated using the following formula, with d_1 being the distance between the silica and the right plate, d_2 being the distance between the silica and the left plate, and d_s being the thickness of the silica Eqn. (2).

$$d_{wc} = d_1 + ds + d_2. \qquad (1)$$

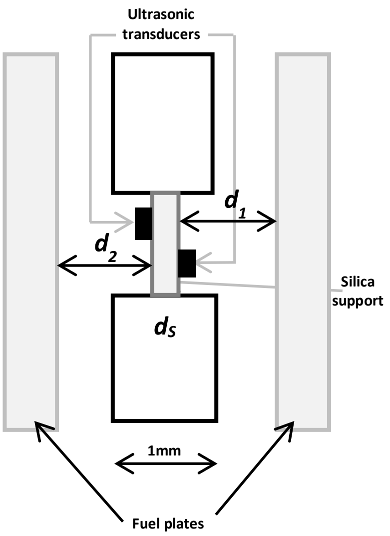

Figure 3. Schematic diagram of the measurement of a channel's thickness.

3.2 High-frequency ultrasonic device

A high-frequency ultrasonic transducer is a multi-layered device comprising a piezoelectric element disk, backing material, matching layer, and coaxial cables for transmission and reception. Fig. 4 illustrates the manufactured transducers. To meet experimental constraints and achieve the desired resolution, LiNbO3 ceramic was chosen for its excellent radiation resistance and vibration properties. The piezoelectric elements were carefully thinned to 35 µm, enabling operating frequencies of around 100 MHz. These elements were then attached to a 400 µm thick high-purity silica support, serving as the delay line. Special care was taken during the bonding process to ensure proper alignment of the transducers [16-17].

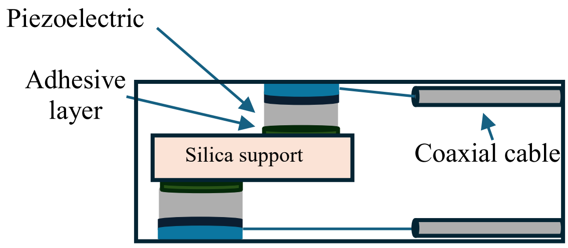

Figure 4. Transducer architecture.

To facilitate the insertion of transducers into the inter-plate distance, they were mounted on one end of a stainless-steel blade, as shown in Figure 5. This blade was meticulously manufactured, adhering to nuclear procedures to ensure material quality, cleanliness, and precise dimensions. The blade used in this study had specific dimensions: 1 mm thickness, 10 mm width, and 1500 mm length. The silica support, including the two active elements, was designed to fit into a hole at the blade's end. Grooves were drilled on both faces of the blade to facilitate cable connections for the transducers. Once mounted, the transducers were connected to a 20 m cable, allowing remote measurements.

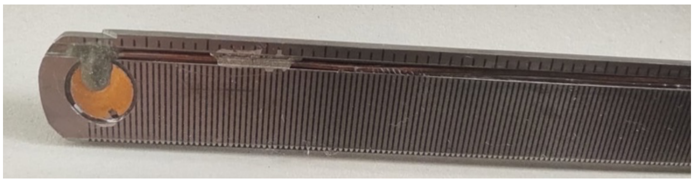

Figure 5. Ultrasonic transducer.

3.3 Instruments

The acquisition system begins with a dual transmitter/receiver electronic board (PXI) designed and manufactured at the University of Montpellier's Institute of Electronics and Systems. This dual pulse generator is optimized to produce high-frequency pulses compatible with transducers operating up to 400 MHz. Additionally, specific electronics enable the excitation of piezoelectric elements after a 20-meter cable.

Electric signals are transmitted through coaxial cables, and the received signals are then sent to a filtering system and a programmable gain amplifier. These signals are captured and converted into digital format using a NI PXIe-5162 acquisition card, chosen for its 2*2.5 GS/s sampling frequency and 10-bit resolution. Subsequently, digital signal processing is performed, with further details provided later.
All electronic board and the control computer are housed in a NI PXI rack, creating a compact and practical system for in-situ measurements. This setup not only ensures convenience but also facilitates procedures required for use in controlled nuclear zones.

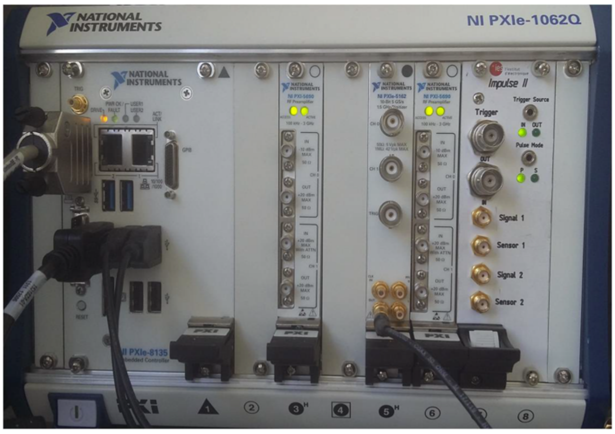

Figure 6. PXI controller with all electronic boards used for the generation, acquisition and processing of high-frequency ultrasonic signals.

3.4 Mechanical holder

Positioning the blade within the water channel is a crucial step in in-situ measurements, especially since the fuel element is stored in a 12-meter deep cooling pool. This experimental constraint necessitates high flexibility in aligning the ultrasonic device. To control and identify the device's position, ILL developed an automatic system. As shown in Fig. 7, this system includes a mechanism that allows translations along two axes to align the ultrasonic device with the fuel plates. It also utilizes motorized reels powered by a variable speed drive to control movement along the z-axis. Additionally, the reel can be operated manually for fine-tuning adjustments and situations requiring manual control.
A wire encoder is also used to determine the vertical position of the blade during measurements. This sensor is directly connected to the PXI rack computer, enabling synchronized ultrasonic measurements with the blade's height in the water channel being measured.

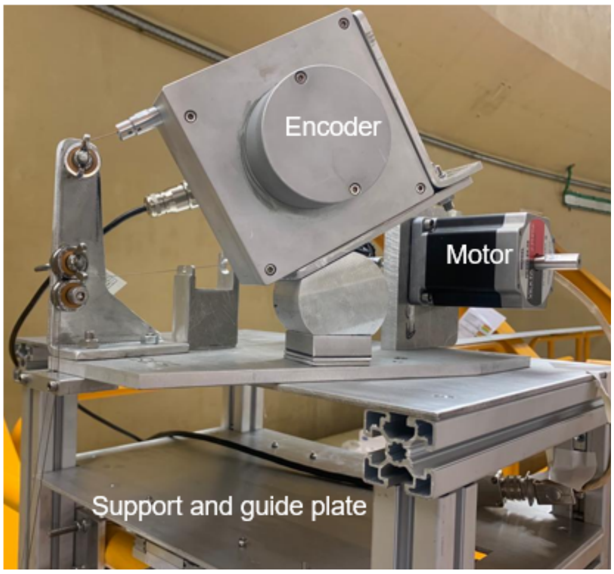

Figure 7. Mechanical holder.

3.5 Measurement principle

The distance measurement is based on a pulse/echo method [18]. The time of flight (ToF) of an ultrasonic wave corresponds to the interval between the emission and reception of an ultrasonic pulse reflected by an object or surface. To determine the distance d to the object, the echo time t is multiplied by the velocity c at which the ultrasonic wave propagates through the medium (Eq. 1).
Due to the transducer structure shown in Fig. 3, two series coexist in the signal. The first series, shown on the left side of the signal in Fig. 8, corresponds to the signature of a transducer positioned in water. This composite signal includes both the electrical excitation of the transducer and the multiple reflections of the initial pulse at the silica/water interface.
The complementary part of this signal is transmitted through the water and received after reflecting off the surface of the fuel plates. The resulting signal corresponds to the right side of the signal in Fig. 8.
To identify the time of flight, an inter-correlation is performed between the two parts of the signal in Fig 8, as indicated in [11]. To achieve this inter-correlation, the two overlapping zones must be separated. This is resolved by

point-by-point subtraction of the first zone with an acquisition made without a plate echo.

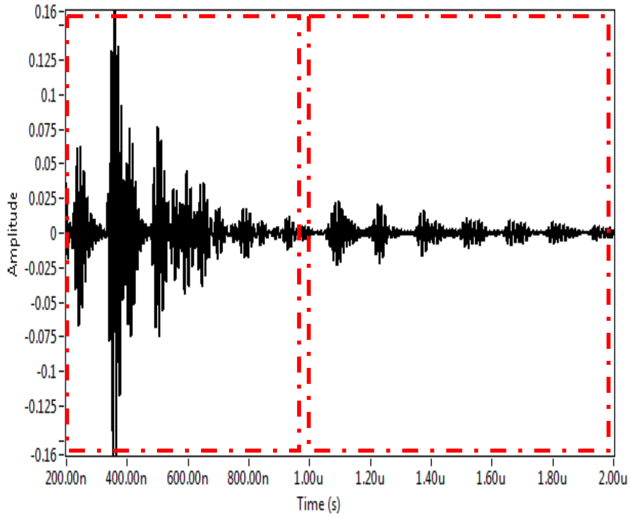

Figure 8. Experimental signal highlighting two series of echoes.

Using a silica delay line that produces multiple reflections allows for inter-correlation with a series of echoes rather than a single echo. This complicates signal processing due to the saturation of the initial echoes but facilitates the detection of the actual time of flight value, as the inter-correlation is performed over a large number of periodic echoes.
The inter-plate distance d_{wc} is then defined by Eq. (2), where d_s is the thickness of the silica layer and d_1 and d_2 are the thicknesses of the water layers on both sides of the blade. A statistical treatment for a given position can also be performed to reduce measurement noise.

4. IN-LAB MEASUREMENT

After introducing the principle of inter-plate distance measurement, we conducted an in-depth evaluation of the complete system to assess the transducer performance and signal processing accuracy for in-situ measurements.

4.1 Experimental bench in the laboratory

We built a motorized test bench with 8 degrees of freedom to ensure parallel motion of the blade to the plates. We first performed tests on a piece of fictitious fuel element, as shown in Figure 9. This allowed us to develop the measurement protocol and verify that the movements measured with the wire encoder, which will be used during on-site measurements, gave satisfactory results.

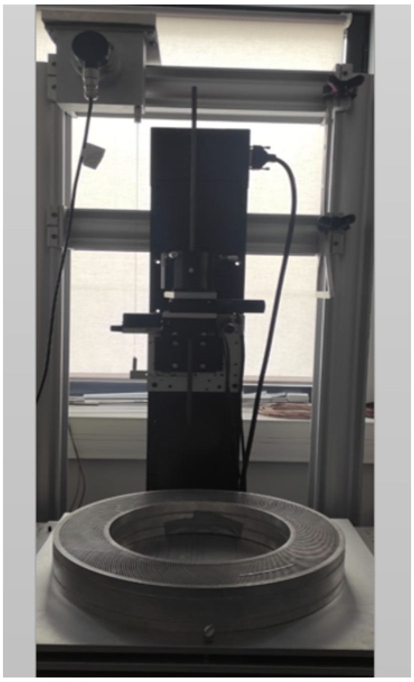

Figure 9. Experimental bench in the laboratory.

4.2 Measurements on a reference sample

This involved creating samples with faces as flat as possible and spaced 1.8 mm apart. To control this inter-plate distance, identical standard shims were machined to micron precision, ensuring the inter-plate distance was as close to 1.8 mm as possible. During a series of measurements, four ascending and descending movements of the device were performed to assess the distance between the plates along the height of this sample. The results of these measurements are displayed in Figure 10, indicating reproducible measurements at each position on a micrometric scale. The average thickness value for the 1.8 mm samples was determined to be 1.82 mm, with local standard deviations of 0.8 µm. There is a global variation of 1.4 µm across the sample's height, attributed to the fabrication process in the laboratory. These laboratory experiments clearly validate the reproducibility and quality of the measurements performed with the designed devices and allow us to consider in-situ measurements.

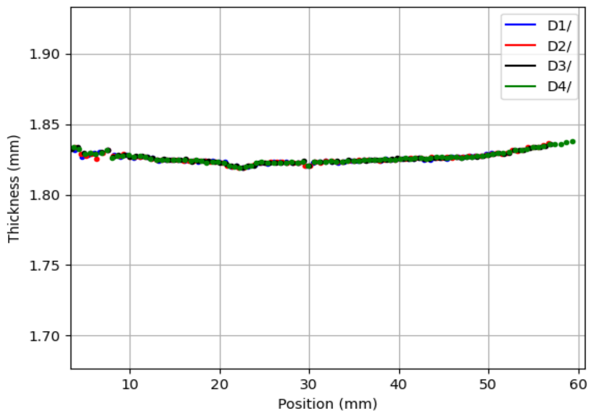

Figure 10. Measurement on a 1.8 mm reference sample.

5. IN-SITU MEASUREMENT

The RHF fuel element at the ILL, produced by CERCA, consists of 280 curved plates welded to two concentric aluminum tubes Fig.11. The fixed distance between two fuel plates, known as the water-channel thickness, is nominally 1.8 mm, allowing cooling water to pass through the reactor structure [19].

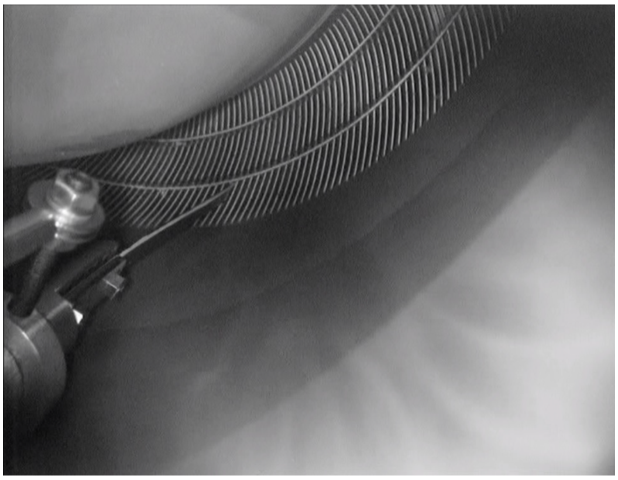

Figure 11. Photo of the insertion of a blade into a channel of the RHF fuel element in the pool.

An in-situ experiment was conducted at the ILL, where a spent fuel element is stored. A radiation-resistant camera was submerged in the pool above the fuel element to observe and control the blade's displacement. The ultrasonic device, equipped with instruments, was attached to a 12-meter support above the water pool. The blade was connected to a supporting system that ensured attachment, alignment, and synchronization with the wire encoder for real-time feedback.

Inter-plate distance measurements were performed on a single channel of the fuel element. Ultrasonic signals were recorded as the blade ascended along the water channel, with signals acquired every 50 ms. Post-treatment extracted high-confidence signals with good SNR from the data, corresponding to accurate estimations of the water-channel thickness. The results, presented in Fig. 12, show thickness estimations over 50 cm along the fuel element depth.

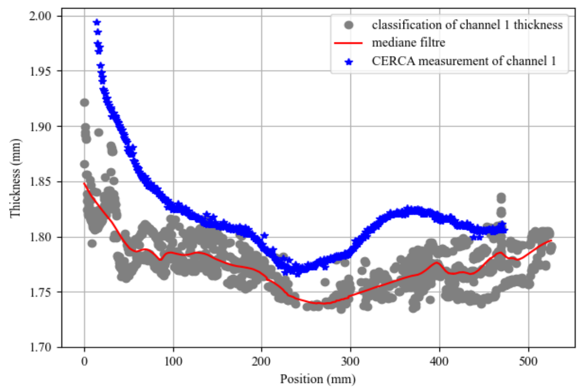

Figure 12. Results of ultrasonic measurements in gray, average in red, and comparison with pre-irradiation measurements conducted by CERCA in blue.

Due to the fuel element's position at the bottom of the cooling pool, alignment of the transducer with the plate surfaces cannot be guaranteed, leading to dispersion in thicknesses. The results, however, provide a good estimation of the water-channel thickness behavior, showing a curved shape with a local minimum between 200 mm and 300 mm.

The thickness estimation is presented as a red straight line along with gray measurement points. This mean behavior confirms a local minimum of 1739 µm in the water-channel thickness at 270 mm from the plate top. Furthermore, the blue curve represents the measurement values provided by CERCA, estimating the inter-plate distance before irradiation, with an average of about 1796 µm. The global profiles for the two sets of measurements were found to be generally consistent. The mean thickness reduction in the first 50 mm is estimated to be around 40 µm.

6. CONCLUSIONS

To summarize, this extensive study outlined the design and application of a specialized ultrasonic transducer for examining the irradiation history of the RHF fuel element. The non-destructive control system utilized the pulse-echo method, enabling the estimation of the inter-plate distance within a fuel element through time-of-flight measurements.

Following the presentation of the system and the signal processing techniques for ToF estimation, various tests and evaluations were performed to verify the transducer's performance and accuracy in measuring this crucial parameter. These assessments helped validate the ultrasonic device and confirm its dependability for in-situ measurements under challenging access conditions.

A dedicated mechanical system was subsequently developed to efficiently transport and position the ultrasonic device in an underwater environment. This system facilitates flexible and agile movements, allowing the remote insertion of the ultrasonic transducer into water channels at a depth of 12 meters. Developed by ILL, this innovative mechanical system provides a solid foundation for inspections, offering more insights into the integrity of the fuel element and enabling measurements in different water channels of the fuel element.

In an initial experiment demonstrating the device's relevance, measurements were taken in one channel of the RHF fuel element. Post-processing was carried out to select signals with a high signal-to-noise ratio. The results presented in the final section were compared to water-channel thicknesses measured by CERCA prior to irradiation. The strong correlation between the two sets of results in the water-channel shape clearly demonstrates the quality of the proposed ultrasonic device and its suitability for future in-situ remote control in radiative environments.

Additionally, this device provided an initial estimation of one water-channel profile of a spent fuel element along 50 cm from the top of the element. The results indicate an average reduction in water-channel thickness of approximately 40 µm.

Since it is not possible to measure elements before irradiation, and to truly compare the measurements taken by CERCA with the ultrasonic measurements, it is proposed to create a demonstration sample that could be measured by both methods to confirm or refute the existing discrepancy between the two methods. Additionally, a further measurement campaign on other channels, compared with pre-irradiation measurements, could help enrich these conclusions.

7. ACKNOWLEDGMENTS

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