ISIR SIMULATION USING CEA-SPECIFIC ULTRASONIC INSTRUMENTATION: TWO MOCKUP STUDIES

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INTRODUCTION: This document presents the results obtained as part of the In Service Inspection and Repair (ISIR) work package of the Sodium Technology and Component (TECNA) project, specifically the CIVA simulations performed on two mock-ups: the matting mock-up and the VISION mock-up. These simulations focus on ultrasonic sensors designed for sodium immersion, developed at Instrumentation System and Method Laboratory (LISM of CEA Energy Division in Cadarache Center). The work was conducted as part of internal research activities [1] [2].

1. OVERVIEW

The main objective is to check whether ultrasonic sensors designed by CEA can detect the notches present in the two mock-ups. Field simulations were first carried out to determine optimal inspection parameters, followed by inspection simulations to assess the actual detectability of the defects.

Historically, LISM at CEA Cadarache has focused on developing High-Temperature Ultrasonic Transducers (TUSHT). These sensors have been used for over a decade on Phénix and have undergone several evolutions to meet new requirements and enhance performance. The TUSHT, designed for use in reactor environments with sodium immersion, is based on a Lithium Niobate piezoelectric material. From this initial design, several variants have been developed—damped, focused, and matrix-type—for both experimental and simulated evaluations.

Two mock-ups were used to simulate various inspection scenarios that may arise in an actual reactor environment. Inspection simulation were performed using CIVA software.

2. SENSORS

The sensors studied here are High-Temperature Ultrasonic Transducers (TUSHT), designed by CEA for immersion in sodium, primarily intended for in-service inspections of Sodium-cooled Fast Reactors (SFR). They are based on lithium niobate piezoelectric elements and have evolved over the years into several variants:

- Undamped TUSHT Ø15 mm: characterized by a high-quality factor and long pulse duration, enabling long-range inspections but offering limited resolution.
- Damped TUSHT Ø15 mm: with lower quality factor and shorter pulses, these allow better defect characterization.
- Focused TUSHT Ø40 mm – RC40 and RC90: incorporating acoustic lenses with radii of curvature of 40 mm and 90 mm, respectively, to concentrate the beam and enhance sensitivity.
- TUM: a matrix sensor composed of 16x16 elements (with 1.5 mm pitch), allowing for advanced imaging via Total Focusing Method (TFM) processing.

These sensors are compatible with sodium immersion and high temperatures, and their performance is evaluated here under typical inspection conditions of sodium environments.

3. MOCK-UPS

Two mock-ups were used to simulate various inspection scenarios that may arise in an actual reactor environment.

The Matting mock-up is designed to reproduce the structural components found at the top of the core in sodium-cooled fast reactors. It includes several welds and machined notches simulating flaws of various orientations and positions.

The VISION mock-up is used for evaluating surface-breaking notch detectability. It consists of four small-width notches with varying depths, representing shallow surface-breaking defects.

3.1. Matting

The Matting mock-up replicates the geometry and materials of the support structures located at the top of the core (matting) in an SFR. It is a 2-inch thick stainless steel block with four side-drilled notches (E1, E3, E4, E6), each placed in different positions relative to a weld zone (welds S1 and S2) as illustrated in Figure 1. These notches simulate planar defects of different sizes.

The main purpose of this mock-up is to study the influence of:

- the inspection configuration (with or without weld crossing),
- the sensor type (size, focusing, damping),
- and the defect location (position and orientation)

on detectability in a realistic context. The simulated inspections aim to reproduce the propagation of ultrasonic waves through potentially complex media (e.g., anisotropic welds) and to quantify signal losses and echo amplitudes.

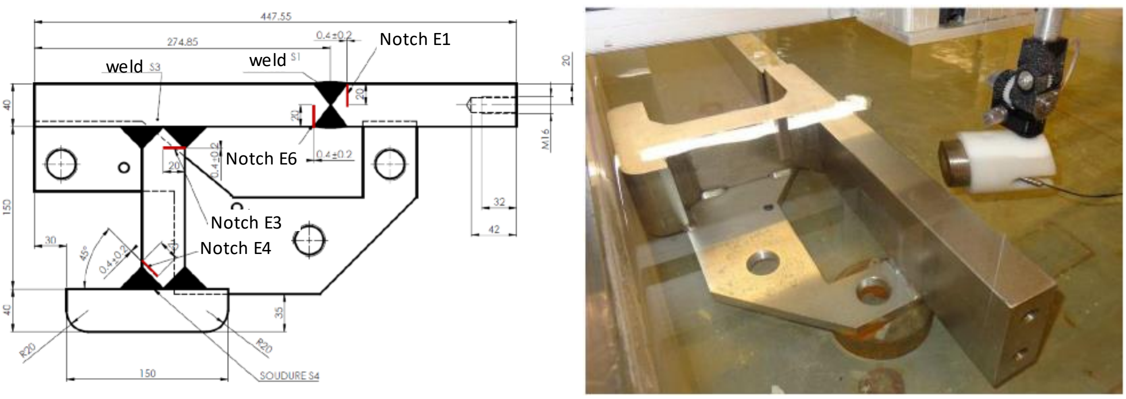

FIG. 1. Matting mock-up: Part design (left side), Mock-up immersed in water photo (right side)

3.2. Vision

Simulations were also conducted on the VISION mock-up to evaluate the sensors' ability to detect surface-breaking notches. The mock-up contains four shallow notches (2 mm deep) with varying widths (0.5 mm, 0.8 mm, 2 mm, and 3 mm). These tests aim to assess the sensitivity of various sensors to very small defects in a simple geometry conducive to imaging.

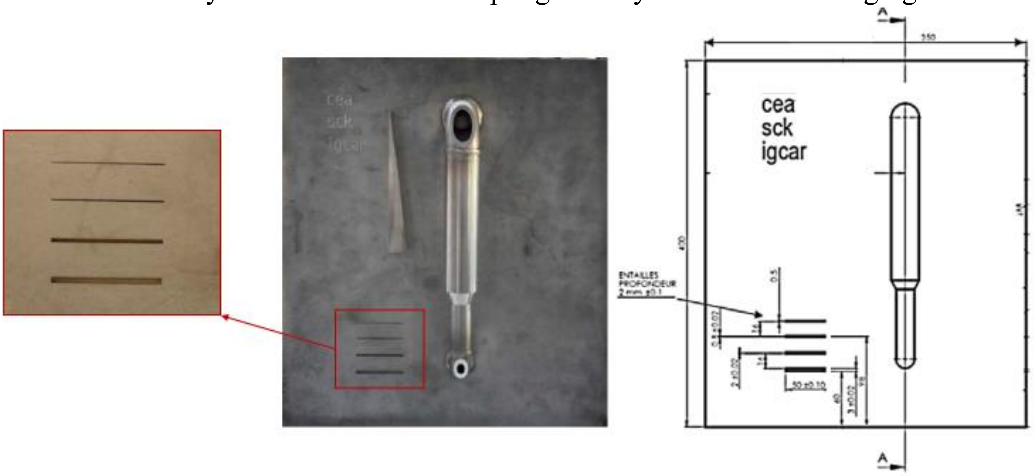

FIG. 2. VISION mock-up

4. SIMULATION RESULTS

4.3. Matting

The simulated inspections aim to reproduce the propagation of ultrasonic waves through potentially complex media (e.g., anisotropic welds) and to quantify signal losses and echo amplitudes.
One of the main considerations for simulations in welds is wave attenuation. The attenuation of longitudinal waves (L-waves) at 2 MHz was provided by the manufacturer. This attenuation varies depending on the angle between the grain orientation and the ultrasonic beam. The attenuation of transverse waves (T-waves) was not provided and was instead estimated from the literature, based on the following criteria [3][4].
Simulations show that correct detection is possible for:

- Notch E6, provided no weld is crossed, with all sensors.
- Notch E3, with all sensors, although undamped versions exhibit significant entry echo spreading.
- Notch E1, without weld crossing, with the TUM, and potentially with the Ø15 mm TUSHTs (damped or undamped).

On the other hand, detection appears to be impossible for:

- Notch E6 after weld crossing, regardless of the sensor.
- Notch E1 after weld crossing, regardless of the sensor.
- Notch E4, in all tested configurations.

It is worth noting that the weld material parameters (attenuation, grain orientation) were defined based on literature data. It is therefore possible that their effect was overestimated in the simulations. Nevertheless, these results suggest that weld crossing remains a major limitation.

In addition, the Ø40 mm TUSHT sensors with RC40 lenses demonstrated insufficient performance and are not considered viable candidates for detecting matting notches. The TUM and the Ø15 mm damped TUSHT appear to be the most promising sensors for this case study.

The Ø40 mm TUSHTs with RC90 lenses may be suitable in certain cases (E3, E6) but remain limited for detecting the other notches, unless a better-suited focusing lens is considered.

4.4. Vision

Simulations on the VISION mock-up were performed for three TUSHT variants: undamped, undamped focused, and damped. In each case, the sensor was positioned at its natural focal distance. A mechanical scan was conducted along two axes, with steps adapted to the desired resolution.

- The undamped, non-focused TUSHT only allows very limited detection of notches: they barely appear on the C-scan, and no clear backwall echo is visible on the B-scan.
- The undamped focused TUSHT significantly improves notch detection on the C-scan, but depth estimation remains difficult due to temporal signal spreading.
- The damped TUSHT enables detection of all four notches on the C-scan, with amplitude variations and time-based depth indicators on the B-scan. However, the beam remains too wide for precise characterization. A version that is both focused and damped would be ideal.

Finally, the TUM sensor, used with TFM focusing at 140 mm from the part, delivers excellent results. Despite a limited mechanical scan, all four notches are clearly detected with good spatial resolution. Time-of-flight analysis allows accurate depth estimation for the larger notches.

5. CONCLUSION

The simulations carried out within the TECNA project have made it possible to evaluate the performance of several high-temperature ultrasonic sensors in sodium immersion, using two representative mock-ups: Matting and VISION.

On the Matting mock-up, notch detection is possible under certain conditions, especially in the absence of weld crossing. The TUM and the Ø15 mm damped TUSHT stand out for their ability to detect notches E1, E3, and E6. However, weld crossing remains a major limitation for all tested sensors. The Ø40 mm TUSHT with RC40 lens was ruled out, while performance of the RC90 could potentially be improved through lens curvature optimization.

On the VISION mock-up, focused and/or damped sensors allow reliable detection of small surface-breaking notches. The TUM stands out for its fine imaging capability using TFM, enabling not only detection but also estimation of defect depth.

These results provide an initial insight into the most suitable sensors for the experimental campaign planned in 2025. However, they should be interpreted with caution, particularly due to uncertainties in the material data used for the simulations (attenuation, grain orientation, etc.). It will therefore be essential to compare these simulated results with upcoming experimental data.

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