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SCCODRA - Development of an innovative corrosion monitoring methodology for the French radioactive waste disposal application

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ABSTRACT: SCCoDRa is an industrial research project which aims to develop characterization and monitoring tools in the perspective of the monitoring program dedicated to the Industrial Centre for Geological Disposal (Cigeo). It has two objectives:

- to screen and develop a potential candidate of a nondestructive testing (NDT) technique (contactless) on metal containers for radioactive waste in order to verify their integrity simply, quickly, reliably, and precisely upon reception at the disposal facility (in the case of ILW-LL). Such a technique must therefore assess the containers for corrosion by means of complete though-thickness mapping.
- to develop one possible methodology for monitoring corrosion in certain metal structures within the facility over time. In particular, this applies to the steel tubes (sleeves) placed inside the micro-tunnels for HLW ("HLW disposal cells"). Here also, the methodology should be based on innovative technology developed in the areas of NDT, electrochemistry, and electrical techniques.

In this paper, we will focus on this second part of the project to present the progress of work relating to guided waves and MURE probe to detect and characterize corrosion on the metal lining.

KEY WORDS: Cigeo, SCCoDRa, NDT, Acoustic emission, Guided waves, corrosion monitoring, SHM.

1 INTRODUCTION

The Industrial Centre for Geological Disposal, or Cigeo, is a deep geological disposal facility for radioactive waste to be built in France. It will serve for disposal of highly radioactive long-lived (HLW) and waste produced by France's current fleet of nuclear facilities, until they are dismantled, as well as from reprocessing of spent fuel from nuclear power plants. The disposal cell for high-level waste consists of a tunnel measuring approximately 70-93 cm in diameter and around 100 m in length. The annular gap between the sleeve and the clay rock is filled with a material that imposes corrosion-limiting environmental conditions (cement and bentonite mixed-based grout, etc.).

Due to reversibility aspect, corrosion is one parameter that could be monitor.

SCCoDRa project focuses on developing innovative tools for testing and monitoring steel corrosion over time.

Ultrasonic Guided Waves (UGW) have shown a potential for non-destructive testing (NDT) of corrosion defects in thin-walled structures such as plates, shells, and pipelines. In addition to their high sensitivity to internal defects, they have the advantage of rapid propagation over long distances and with very little dissipation, allowing inspection of large installations and hard-to-reach areas [1] [2].

Over the last two decades, several guided waves inspection (GWI) systems have been developed and are widely used today to inspect large industrial structures. However, these techniques, generally based on the principle of pulse-echo ultrasound, remain global and often qualitative. They may allow the detection and localization of corrosion defects without providing information on the shape and dimensions. To overcome these limitations, a new concept, known as Structural Health Monitoring (SHM), has been developed over the past 15 years. It consists in the implementation of a network of embedded sensors, which automatically and continuously monitor the condition of its host structure. It enables the observation of changes in the physical and/or geometric properties of the in-service structure. The application of an inverse transformation on all the acquisitions allows reconstructing the properties of the environment and determining the characteristics of the damage [3] [4].

Acoustic Emission (AE) have also shown a potential for NDT of corrosion monitoring. In the literature, several authors have studied the detection as well as the identification of acoustic emission sources related to corrosion. It appears that the emissivity of the sources significantly depends on the nature of the material and the exact progress of the crack or the corrosion processes [5]. In summary, from all the work carried out on the subject of corrosion monitoring by acoustic emission [5-14], we can retain that corrosion generates AE, but the most emissive corrosion phenomenon is the stress corrosion cracking (SCC). The qualitative detectability of corrosion depends on the kinetics, the degree of corrosion progress and the propagation medium.

Among electrochemical methods, zero-current potentiometry is widely used for corrosion monitoring. A new potentiometry technology called MūRE ™, developed by Politecnico di Milano University (patent: N. MI 2004-A00969) and produced by the firm CESCOR presents many advantages in terms of corrosion monitoring of structures like pipes, steel frames, etc. It is a series of linear electrodes in nickel or stainless steel used as a pseudo reference to make distributed measurements of corrosion potential of steels. Studies in the field of civil engineering using MūRE sensors [15] have shown that the hydration of concrete and the addition of the chlorides influenced the potential measured against a new structure.

SCCODRA project, plans to combine the global (GWI acoustic emission and MURE) and local (Acoustic emission, Electrochemical Noise, Linear Polarization Resistance …) techniques in order to achieve a more optimal monitoring steel corrosion. in this paper, we focus on global corrosion monitoring techniques.

2 GLOBAL CORROSION MONITORING

Global corrosion monitoring consists of collecting information on practically the entire structure via sensors distributed over the surface of the tube. The global techniques selected are:

- Guided waves imaging (GWI)
- Acoustic Emission (AE)
- Distributed corrosion potential via MURE probe

2.1 Guided waves imaging

Different methods of reconstructing corrosion damage with guided waves are implemented. In this paper, the numerical or experimental results of different reconstruction algorithms (topological imaging, RAPID, QRAPID) will be presented.

Figure 1 shows the schematic of the reference setup used for the experimental study, knowing a 1002 × 1002 × 4 mm aluminum plate instrumented by two sets of 16 transmitters and 16 receivers facing each other and driven by a multiplexer.

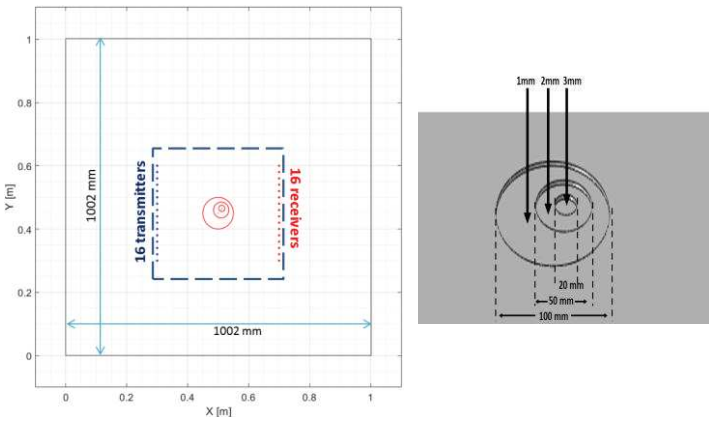


Figure 1. Experimental setup for mimicking corrosion damage (left), detail of the irregular defect (right)

The area of interest in a 400 × 400 mm centered square in order to avoid the interferences from the edge-reflected wavefronts using time windowing of the ultrasonic signatures. The excitation frequency of the transmitters is $f = 312.5$kHz. An irregular defect with three different dimensions as well as three levels of thickness-loss was progressively introduced in order to simulate the monitoring of a growing corrosion defect.

2.1.1 Numerical results with topological imaging

Topological imaging consists in estimating a cost function of the difference between the reference signals obtained by a direct numerical model of the pristine structure and the measurements made on the supposedly defective structure. The difference, containing the signature of the defect, is time-inverted and injected into the so-called adjoint model. An analysis of the simulated field, refocused on the echogenic zone, allows the topology of the model to be modified by inserting the virtual defects. The latter is used to evaluate the deviation and in turn generate a modified model.

The version of the method used in this work is the Time Domain Topological Energy method (TDTE), which enables to consider all the diffraction physics in a direct, simple and unrestricted way, regarding to the nature of the material or to the dispersive and multimodal nature of GUW. It requires only one iteration while offering a reconstruction of every discontinuities with an improved signal-to-noise ratio.

To illustrate the method, we built a numerical model of the problem using a slightly different configuration, namely a rectangular 400 × 400 × 5 mm carbon-steel plate, in which the introduced corrosion as the same characteristics of size and the same proportions of depth (25% to 75% of the nominal thickness). To generate a purely monomodal propagation of the first fundamental symmetrical Lamb mode (S0), we insonify the plate with edge-mounted piezoelectric transmitters. Figure 2 shows the obtained result of the topological energy reconstructed using the sum of four simulations for which the insonification is done by a linear transducer array placed on the left, top, right and bottom edge respectively, while the theoretical profile appears on the right and side.

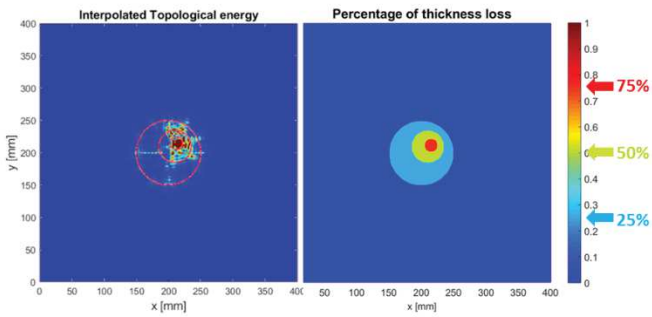


Figure 2. Topological imaging of an irregular defect. Summation of the results from 4 insonifications (left), expected thickness-loss image (right)

Having carried out multiple insonifications in different directions makes it possible to define the contours of this defect relatively well and in particular to identify the most critical area Although this ideal numerical case provides a very good resolution, until now, this technique only shows qualitative information about defects. Therefore, the aim of the next part is to derive quantitative information from the reconstruction of corrosion damage using a novel tomographic algorithm.

2.1.2 Experimental results of tomographic reconstruction

In the literature, lots of tomographic reconstruction techniques have been documented, all based on advanced signal processing techniques exploiting approximations underlying the physical phenomena related to wave propagation in the structure. The principle is to observe the variation of one or more parameters (attenuation, time of flight and/or phase shift) sensitive to inhomogeneity, from different angles. The measurements are generally performed for each element of a sensor array, completely or partially surrounding the area to be inspected. Then, a treatment of these measurements, according to a given approach, allows to accentuate the characteristics of the damaged area.

The probabilistic method known as RAPID [16] has proven advantageous for structural health monitoring using permanently mounted piezoelectric transducers. It offers great flexibility in the choice of array geometry, simplicity of implementation and allows detection and localization of defects with few sensors. RAPID translates the changes in the characteristics of the ultrasonic signals acquired in the healthy and damaged state into statistical data. Then the probability of the presence of a defect, is spread out as an ellipse whose focus positions are occupied by the transmitters and receivers and whose ellipticity is controlled by a shape parameter β. By summing the probability densities over all the elements of the network, a mapping of the region of interest is obtained.
Figure 3 shows the progression of the reconstruction using the RAPID approach. Despite the simplicity of implementation of the method, the reconstruction suffers from artefacts due to the raw summation of the rays and does not allow the direct quantification of the thickness loss.

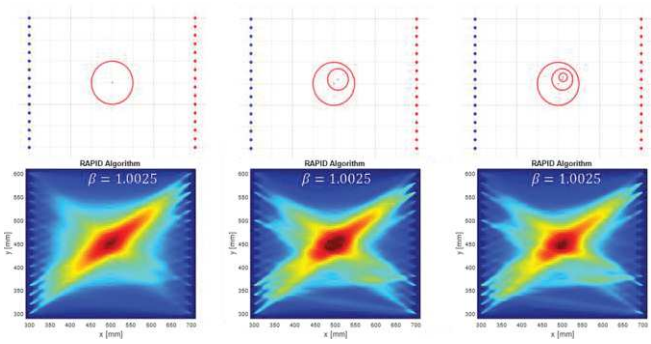


Figure 3. Tomographic reconstructions using RAPID

On the other hand, research on the classical filtered back-projection (FBP) method [17] has shown that it is possible, by means of a set of projections, to estimate the thickness loss with good precision [18]. However, the method has some practical drawbacks. It requires a specific scanning scheme (parallel or fan) and a very large number of projections, which makes it unusable for our application.

Thus, we propose an innovative GWI technique for the quantitative evaluation of corrosion defects in plates and pipelines, called QRAPID. The idea is to combine the classical FBP method and the RAPID algorithm. Using an appropriate mode and frequency selection, the time of flight is used to estimate the thickness loss between each pair of transducers. This is back-projected in the form of an ellipse linking the transducers. The sum of all the contributions of a transducer array gives a picture of the spatial distribution of the thickness loss. The resulting technique benefits from the advantages of both algorithms. Reverse projection in an elliptical pattern instead of a linear one allows to overcome the low fill factor of the FBP due to insufficient measurement data. Thus, a tomographic image can be obtained with fewer transducers. In addition, the filtering process reduces artifacts and increases the accuracy of the reconstruction. In addition, the simplicity of the summation gives the method great flexibility with respect to the geometry of the array. Applied to the same experimental incremental damage, the reconstruction obtained with QRAPID is shown on Figure 4.

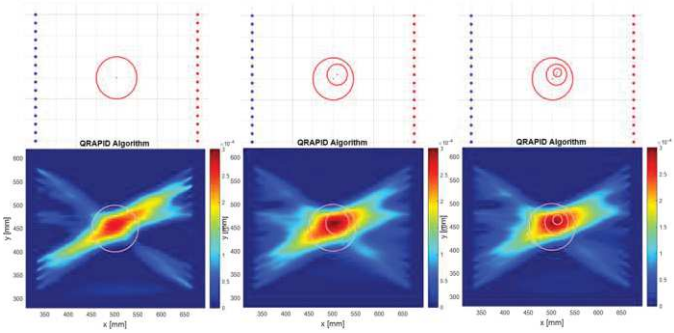


Figure 4. Tomographic reconstructions using QRAPID

2.1.3 Conclusions

The results of the reconstruction of experimental measurements with QRAPID present a fairly good agreement with the theoretical values of the loss of thickness, knowing that the three images presented in Figure 4 have the same color scale that can be quantitatively adjusted on the effective loss of thickness. The estimates obtained with a parallel network sometimes show an excess thickness resulting from incomplete measurement angles. A threshold has been applied to correct this aberration. Otherwise, a horizontal parallel network could have been added, as was done in the numerical simulation described in the previous paragraph.
Unsurprisingly, the resolution is not as good as that promised by a method such as topological imaging, knowing that the smallest details of the defect are smaller than the Fresnel length, i.e. $\sqrt{\lambda L}$ (equal to 108 mm here) with λ the wavelength and L the longest distance between transducers, which serves as a theoretical limit for tomographic reconstruction with this method.

2.2 Acoustic emission

The acoustic emission technique will be used mainly for the detection of progressive degradations such as stress cracking generated by corrosion. A first step consists in carrying out local analyzes at the laboratory scale in order to extract acoustic signatures specific to degradation phenomena. Then, the second step consists in selecting an acquisition chain adapted to the measurement environment (size, radiation, electromagnetic noise, ...).

AE sensors based on piezoelectric transducers (PZT) are to-date the most diffused ones. However, the intrinsic limitations of PZT transducers have limited the fields of application of these sensors in many industries. This is because a standard piezoelectric sensor has a limited operating temperature and is not usually suitable for cryogenic or high temperatures, and it is not robust against humidity, nuclear radiation and electromagnetic interferences. In such context, fiber-optic transducers have been investigated through the years as a possible solution. Thanks to their passive nature, fiber optic sensors (FOS) can outperform electrical sensors in challenging operational environments.

The performance of two types of acoustic emission sensors, namely optical and PZT, were investigated [19]. The experiments were conducted by Optics11 in collaboration with CETIM, and the sensors were compared with regard to their sensitivity, localization accuracy and precision, directivity, and

their AE induced waveforms. The results of the experiments showed strong comparable performance between the sensitivity of the two sensor types, which were consistent along several measurements. Further, both sensor types had a uniform amplitude response to AE events at different angles from them, making the positioning of the sensors independent from the test setup or the measurand signals. The localization accuracy and precision of both systems to the AE events in a triangular setup were also comparable. In particular, the localization accuracy of the optical sensors in all the performed tests was below 1cm. These results show that all the above-mentioned properties retrieved for the FOS are in accordance with the PZT performance despite the different resonance frequencies and principle of operation.

2.3 Measurement of distributed corrosion potential

2.3.1 Principle of the MURE probe

The MURE probe is made up of a series of linear nickel or stainless-steel electrodes used as a pseudo reference to carry out distributed measurements of the corrosion potential of steels. The use of this technology makes it possible to continuously map the variations in potential along the structure with a small sensor (depending on the structure to be studied) and with thresholding, it is possible to locate the areas of activity to be monitored. It also allows the study of anodic and cathodic behavior, the appearance of bites and the presence of stray current.

2.3.2 Presentation of the assembly and the probe

To measure the potential along the pipe, a MūRE ™ probe was positioned along a two meters long pipe. The surface of the pipe was first roughly polished in order to remove the corrosion products present on the surface. The pipe was positioned in a cement grout for reproduce radioactive waste disposal environment.

Table 1. Cement grout composition

Elements	Quantity (kg/m^3)
Cement	126
Silica fume	126
Bentonite	33,6
Hydrotalcite	8,4
Tap water	881

MūRE™ is a permanent pseudo reference electrode, made for reinforced concrete structures to detect corrosion in early stage. It is a series of linear-Ni/Ti-made-electrodes, working as pseudo-reference electrodes to measure the local potential of steel. This probe was initially design for monitor corrosion of steel in reinforced concrete.

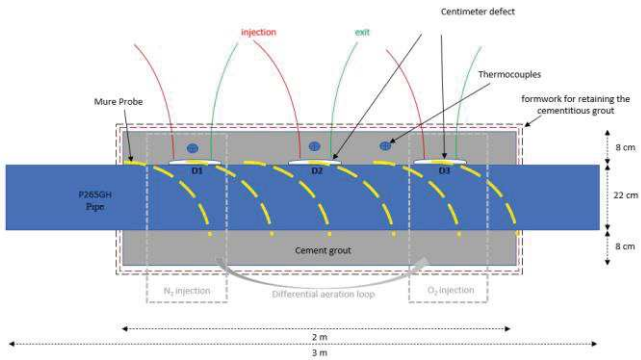


Figure 5. schematic representation of the assembly

The purpose of the assembly was to determine if the initiation of localized corrosion or modification of environment which can cause higher corrosion rate can be detected. For the purposes, corrosion condition which can cause these phenomena were created. Filling defects and capillary were positioned inside the assembly and permit to modify locally the environment thanks to injection. 6 measurement points are presents in the assembly, they are on either side of each of the filling defects. Mure 1 and 2 is around defect 1 (D1), Mure 3 and 4 around defect 2 (D2) and Mure 5 et 6 around defect 1 (D1),

2.3.3 Results

After a slow increase of potential during the first three month (increase of 1 or 2mV/day), the potential stabilized at close potentials for the 6 pseudo references (difference less than 10mV).

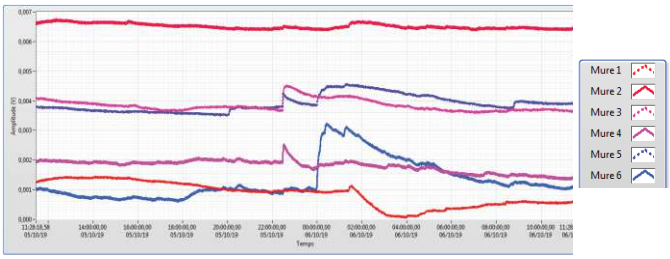
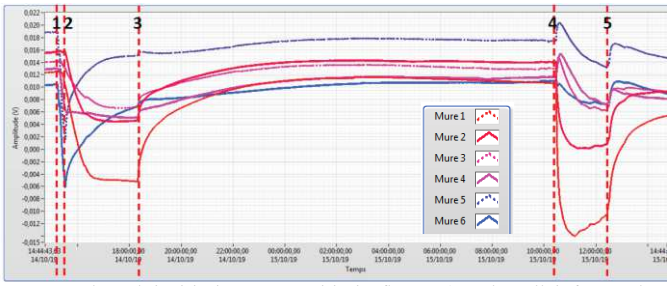


Figure 6: Potential measured after 87 days (potential is done versus MūRE ™probe)

The potential increase is about 100mV between the first days and the 87 days. This increase in potential can be explained by the formation of a layer of corrosion products on the surface of the steel. The measured potential is relatively high for a carbon steel (≈0 Vs MūRE ™) but this value can result from the pseudo passivation of the steel surface which can take place due to the high pH (pH≈10,7).

An aeration cell was created in order to determine the sensitivity of the probe on this phenomenon. On one side, solution where 0_2 is bubbling is injected in the defect D3. On the other side, solution where N_2 is bubbling is injected in the defect D1. The re-release of the differential aeration test was divided into 5 steps, different injections speeds were tested but only one is presented above.



Step 1: N_2 and O_2 solution injection, average N_2 injection flow rate (around 10 ml/min for N_2 and 10 ml/min for O_2)
Step 2: no action
Step 3: cut off circulation of the N_2 solution
Step 4: Injection of N_2 + O_2 solutions - average injection flow rate N_2 (identical reference 1)
Step 5: Flow stop

Figure 7: Measured potential thanks to MūRE ™ probe during created aeration cell (potential is done versus MūRE ™probe)

As expected, a decrease of potential was observed for the probe close to deareted area (step 1, Mure 1 and 2 closes to D1). It is also interesting to observe that Mure 3 and 4 (close to defect 2) have a decrease of the potential even if they are 0.5m to the perturbation (O_2 injection). When only O_2 is injected in D1 defect (between step 3 and 4), the potential goes back to potential previously observed before experiments. This phenomenon shows that the system is in aerated condition before O_2 injection.
Other perturbation of the environment as chloride addition (not presented in this document) results of potential perturbations and so can be monitored thanks to MūRE™ probe.

2.3.4 Conclusion

Monitoring of a part of pipe was possible thanks to MūRE ™ probe and has the advantage of having a small footprint of the probes and the system.

At this stage, the results made it possible to discriminate the differential aeration zones and in particular those presenting a risk of corrosion, namely those with the most electronegative potential, positioned on the N_2 injection side, in accordance with expectations.

Finally, considering these results, the MūRE ™ technology being only qualitative, the results showed its ability to locate an active surface with a precision of the order of a few tens of centimetres (spacing between two probe turns) under the conditions of study. However, a good knowledge of potential variations is necessary in order to be able to correlate them with the phenomena occurring.

This technic can be coupled with CND method in order to have more quantitative methods.

3 CONCLUSION

This work presented the developed methodology for the corrosion monitoring of steel tubes (sleeves). This methodology is based on a complementarity between global and local techniques in order to optimize the resolution as well as the robustness of the monitoring. In this paper, in this paper we have presented only the global methods (GWI and Mure).

First results of GWI highlight the potential of this method to carry out a quantitative cartography of the structure thickness. Analyzes are in progress in order to select the reconstruction algorithm offering optimal resolution (topological imagery, RAPIDE, QRAPIDE, ...). Other global techniques such as AE or OCP via the MURE probe allow early and distributed detection of several corrosion phenomena (pitting, SCC, etc.). However, the integration of measurement chains such as piezoelectric in a highly radioactive environment has many limitations (high temperature, electromagnetic noise, radiation, etc.). Work is underway to adapt the measurement systems, particularly in the case of AE using optic fiber technology.

In addition to applications in the nuclear industry, these technologies could be used in sectors such as "Oil & Gas" as well as growth sectors such as marine renewable energy. These industries have to meet testing and monitoring requirements for infrastructure in hostile environments and with long operating lives (25 to 30 years in the case of marine renewable energy).

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