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High-Temperature Ultrasound NDE Systems for Continuous Monitoring of Critical Points in Nuclear Power Plants Structures

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ABSTRACT

High temperature pipe cracks are the root of a steam power failure in the EU typically every 4 years, resulting in loss of human life, serious accidents and massive financial losses. According to IAEA's Reference Technology Database, such an event on a nuclear power plant has an average cost of €120 million, including outage costs, emergency repair costs, insurance and legal costs. Since only one growing crack is needed to cause a major failure, they have to be inspected and monitored thoroughly.

Breakdowns at extreme conditions (e.g. 580°C, 400 bar) are a result of two major weld failure modes: a) creep cracks near pipe welds; b) fatigue cracks on pipe welds. Current maintenance practice is to proceed with repairs on a detected crack according to its severity. For cost reasons, cracks that are not judged as severe enough will not be repaired. Crack severity judgement is based on its probability to cause a failure and this probability is derived taking into account the crack size and operational lifetime. More variables such as operating temperature and vibrations may rarely be found in other studies. Recent data from fracture mechanics statistical studies shows this connection between the size of a crack on a nuclear power plant pipe and its probability to lead to a failure.

To deal with the above problems two Structural Health Monitoring (SHM) systems have been developed and they are presented in this work. These systems are able to achieve continuous operation for an extended time period at operating temperatures of nuclear power plants. The developed systems employ novel phased array (PA) ultrasonic and ultrasound guided wave (UGW) probes able to withstand and continuously operate even up to 580 °C. The systems are designed to be permanently mounted on superheated steam pipes, at locations of known defects and to continuously monitor their size. However, this supposes that defects will have already been detected by a traditional method during an outage. The PA transducers are placed according to the Time-of-Flight Diffraction (TOFD) technique's topology, thus creating a novel configuration, while the UGW transducers are placed on a stainless steel ring in a circular array configuration. These configurations can enable continuous tracking of cracks growth with high accuracy, enabling maintenance crews to estimate the severity directly and not through statistics.

Keywords: *nuclear power plants, high temperature ultrasound, phased array, guided waves, signal analysis*

1 INTRODUCTION

The recent accident in the Fukushima nuclear power plant has made governments all over the world re-discuss and re-evaluate the safety procedures and regulations for their nuclear power plants. The outcome of those re-evaluations is not yet precisely defined – nevertheless the final solution should not neglect that there is a non-negligible amount of data showing that failures and accidents in NPPs become more probable as the plants age. A large portion of active NPPs in the world are close to the end of their operating license, which is generally 40 years. The economically sound solution seems to be granting the license extensions and increasing the safety levels by additional inspection and repair activities. A continuous online monitoring of the structural health monitoring of such facilities and incorporated logic for prediction (modelling) of transient failures/cracks behaviour turns out to be one of the most prospect tools [1]. For such a solution one has to have systems that are functional and resistant to harsh working environment of NPPs. For ultrasound monitoring systems of that kind, the high operating temperatures are one of the key obstacles to overcome, due to generally low Curie temperatures of commercially available piezoelectrics and to weak ultrasound reception capability of piezoelectrics at high temperatures.

Outages in the power plants (both nuclear and classic fuel) involve shutdowns of the power plant, erecting of scaffolding and removal of insulation to gain access which is a significant part of the inspection cost. Generally, the higher the pressure and the temperature of the steam entering the turbine, the greater the efficiency of the electrical generator; thus the goal of both manufacturers and operators is to carry as hot and more pressurized steam as possible from the boilers to the steam turbines. As a result, a typical thermal power plant (0.5 GW) has approximately 4km of pipes operating at temperatures of 580°C and pressures of 400bar, while the steam generators in typical nuclear power plants operate at temperatures up to 345°C and pressures of 155 bar.

If defects are identified during the outage the plant operators need to make a decision to either replace the defective pipeline or decide that the defect is not severe and monitor it closely at the next outage. However, uncertainties in the calculation of the lifetime of these superheated steam pipes that contain a minor defect may potentially have catastrophic consequences.

This paper presents the developing work on two different and partly complementary high temperature Structural Health Monitoring (SHM) systems that utilize high temperature Phased Array (PA) probes in Time of Flight Diffraction (TOFD) configuration to continuously monitor the defect growth over time (and thus inform the plant operator if the defect reaches a critical size so that the plant can be shut down and maintenance can take place before failure) and a long range ultrasound testing (LRUT) system for NDE of NPP piping at operating temperatures. The systems can provide early warning mechanisms. The first system consists of high temperature PA probes, ruggedized PA pulser-receiver unit, and signal processing & visualisation software, the other (LRUT) system is similar, the only difference being that there is an array of high temperature single element shear-wave ultrasound probes aligned in a stainless steel ring (collar) that can be wrapped around a hot pipe.

2 HIGH-TEMPERATURE UGW PROPAGATION MODELLING

The behaviour of the ultrasonic guided waves (UGW) for the LRUT at room temperature, 260°C and 595°C was modelled for this work. Frequencies varying between 10-200 kHz were investigated. Steel pipes are ideal for application of guided ultrasonic waves as they require an elongated medium to propagate – the wave propagation is not dependent only on the material from which the pipe has been manufactured but also on the size and thickness of the pipe. The pipe studied was 8 inches, ANSI Schedule 40. Calculation of dispersion curves for three temperatures (room temperature, 260°C and 595°C) has been carried by using literature available material data for steel. Three wave modes have been selected: L(0,1), identified as a candidate during the preliminary investigation, L(0,2) and the torsional vibration mode T(0,1) (Figure 1). The transient analysis simulations were performed using the same pipe material and geometry as for the dispersion curves calculation. The crack was selected to be 1mm wide and for practical reasons covering 90 degrees of the circumference. Different frequencies have been investigated (60kHz, 100kHz, 150kHz, 200kHz). The excitation was applied axially on 32 points equally distributed in the circumference of the pipe (the real configuration of transducers in the UT collar).

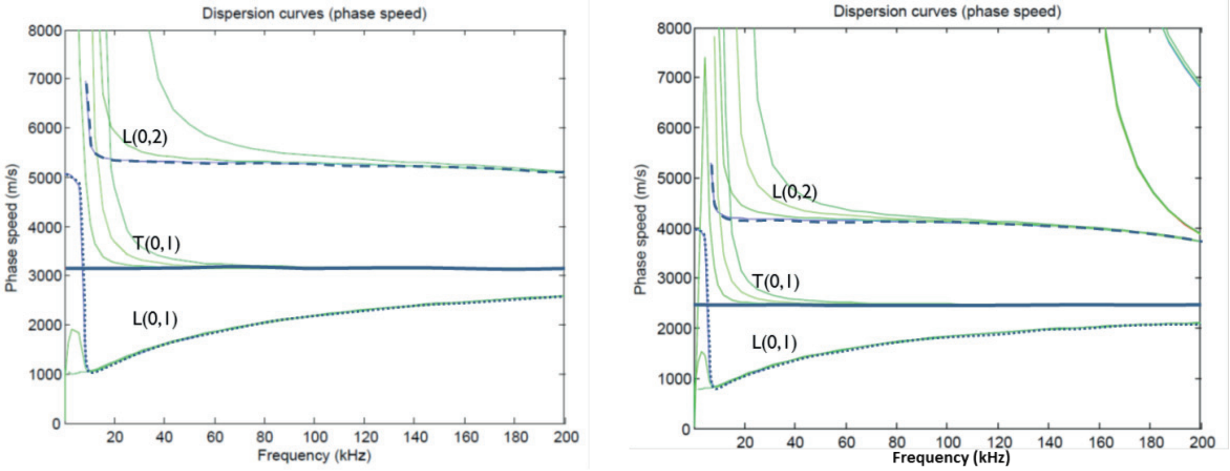

Figure 1: Dispersion curves generated for 8 inches pipe at 260°C and 595°C. Further material data for different Poisson's ratio was also calculated to investigate impact of Poisson's ratio to the dispersion curves

The torsional (shear) mode T(0,1) was finally selected to be exploited in the transducers design due to its non-dispersive behaviour throughout the frequency range of interest.

3 PA-TOFD PROBES

PA-TOFD is the combination of the pitch-catch technique with the generation of a range of angle beams. The transmission and the reception of the sound are separated by two transducers positioned on either side of the weld. It has been shown that the focused ultrasonic phased array was capable of detecting diffraction signal from crack like flaws, enabling detection and through wall sizing [2]. Therefore the PA technology combined with the TOFD principle allows coverage of a large weld volume and the heat-affected zone (HAZ) with a single probe set and reduces the need to use several probe sets and mechanical scanning. This presents the advantage of simplifying the inspection implementation.

Figure 2 presents the PA-TOFD concept, where one linear PA probe operates as a transmitter focusing the sound and the other as a focused receiver.

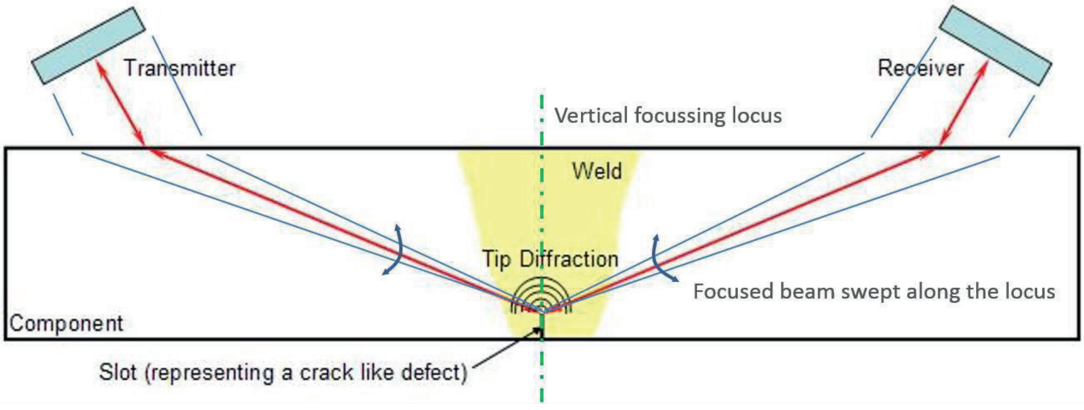

Figure 2: PA-TOFD concept

The inspection of the weld is to be performed while the pipe is in service. During the operating condition, the worst-case temperature at the surface of testing is around 580°C.

Unfortunately, commercial PA probes that can operate at these high temperatures (580°C for thermal and 345°C for nuclear power plants) are rare or non-existent. For example, PZT5A piezoelectric materials can operate on maximum temperatures between 242°C and 350°C, which makes them unsuitable for constant monitoring of pipes in nuclear and thermal power plants. Hence, it was vital to develop high-temperature probes by selecting suitable piezoelectric materials and other components that can withstand temperatures approximately up to 580°C, and design, build and test prototype probes under laboratory conditions.

The PA probes use piezoelectric elements for generation and reception of ultrasound needed for inspection and monitoring. Several high temperature piezoelectric materials were considered [3,4], taking into account their respective Curie temperature, piezoelectric charge constant d_{33}, piezoelectric voltage constant g_{33} and electromechanical coupling factor k_t. Gallium orthophosphate ($GaPO_4$) has been selected for further investigation via high temperature impedance measurements, with results given in Figure 3.

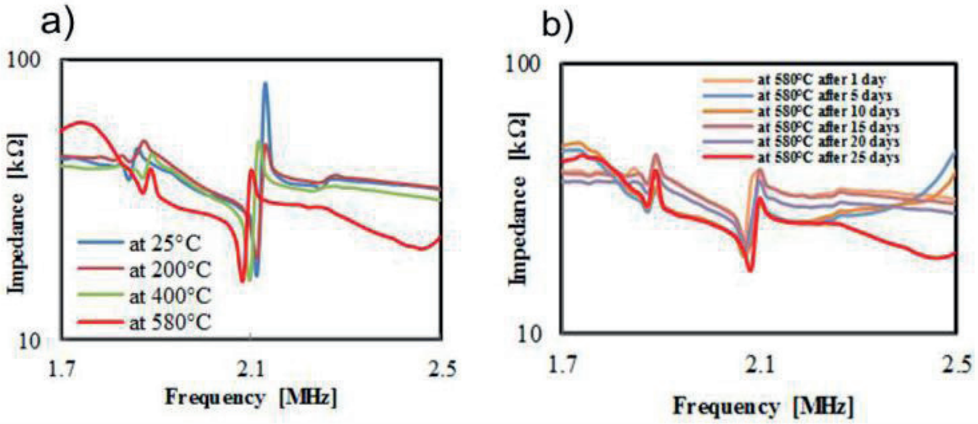

Figure 3: Frequency dependent electrical impedance of the tested $GaPO_4$ array element with the respect to: a) the temperature, in the temperature range from 25 °C up to 580 °C; b) elapsed time on constant temperature of 580 °C, ranging from 1 to 25 days. Five elements were used for the characterization, with the following dimensions: 1 mm thickness, 3 mm width and 12 mm length

It can be seen that the impedance values at resonant and anti-resonant frequencies vary with temperature, i.e. the impedance at resonance decreases with increase in temperature. There are no significant changes in the resonant and anti-resonant frequencies or their corresponding impedances before and after the exposure to temperatures up to 580°C. Exposing the $GaPO_4$ elements to high temperatures for extended periods of time (up to 25 days) has shown that the resonant and anti-resonant frequencies remain stable, while the impedances at these frequencies exhibit a decrease in value. However, the difference between the impedance values at critical frequencies remains constant over large exposure times, and any decrease in absolute values can be mitigated by varying the gain of pulser-receiver electronics.

The final PA probe CAD design is shown in Figure 4, with specifications given in Table 1.

Table 1. HotPhasedArray probe parameter specifications

Type of transducer	Linear phased array
Number of elements	16
Element width	0.9 mm
Gap between elements	0.1 mm
Element pitch	1 mm
Center frequency	5 MHz

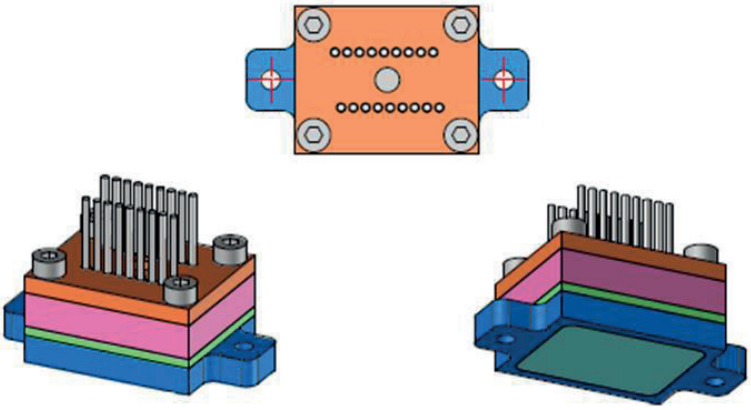

Figure 4. CAD design of the prototype high temperature phased array ultrasound probe

Two prototype PA probes (Figure 5) were then manufactured using $GaPO_4$ single crystal elements according to the design presented above.

Figure 5: Two manufactured high temperature PA ultrasound probes using piezoelectric $GaPO_4$

The two PA probes were mounted to two wedges made in stainless steel, placed onto a pipe section (P91 steel) representing the pipe from a power plant and tested (Figure 6).

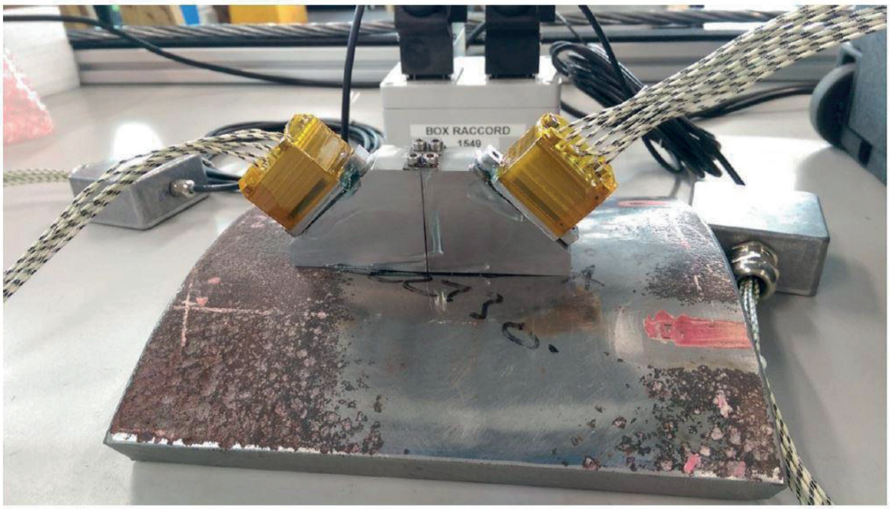

Figure 6: Two $GaPO_4$ high temperature PA ultrasound probes mounted on two stainless steel wedges and placed on a P91 steel pipe for PA-TOFD configuration measurements

4 HIGH-TEMPERATURE ULTRASOUND SHEAR WAVE TRANSDUCERS

For the other, UGW LRUT SHM system, piezoelectric lithium niobate in single crystal form was selected for development of high temperature transducers. The high temperature piezoelectric properties of the $LiNbO_3$ were studied previously – it was observed that the samples retained its piezoelectric properties at up to 600°C [5,6]. The performance of the transducer made for this work was examined by pitch-catch experiments taken at ambient (20°C) and high temperatures (up to 600°C). The $LiNbO_3$ samples were used with dimensions of 13mm x 3mm x 0.5mm, and gold coated on both sides of the length-width plane. The samples were placed in a specially designed sample holder inside a furnace. The high temperature impedance measurements were sequentially performed in 50°C intervals beginning at 50°C up to 600°C. The characteristic frequencies, capacitance, density and dimensions of samples were used to calculate the dielectric, elastic and piezoelectric coefficients. Subsequently, complete high-temperature prototype transducers were manufactured and tested ultrasonically up to 600°C. This was carried out on a steel rod at 70 kHz. Figure 7a shows the temperature dependence of the piezoelectric coefficient d_{15}. The increase of d_{15} from 350°C to 600°C means that the transmission quality of the material should improve. Figure 7b shows the temperature dependence of the piezoelectric coefficient g_{15}. The decrease of g_{15} from 350°C to 600°C means that the reception quality of the material should deteriorate.

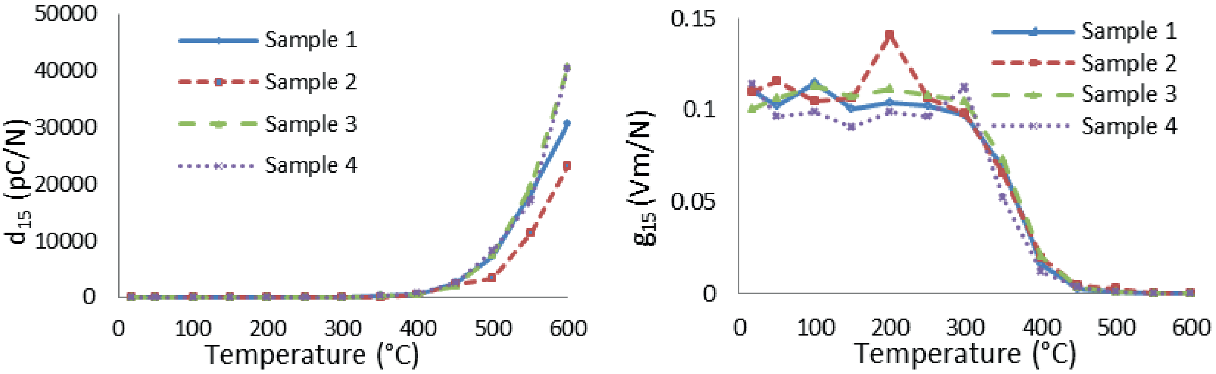

Figure 7: The temperature dependence of the lithium niobate samples piezoelectric coefficients a) d15; b) g15.

The transmission and reception quality of the transducer up to 600°C was measured using a pitch-catch set-up. A 1.5m long square steel bar (12mm^2) was used as the wave guide. On one end a PZT element was permanently fixed on to bar, and the other end was placed inside the furnace. The peak-to-peak amplitude value of the fastest arriving wave mode was used as an indication of transducer's performance. Measurements were taken from room temperature (20°C) up to 600°C, at 50°C intervals (Figure 8).

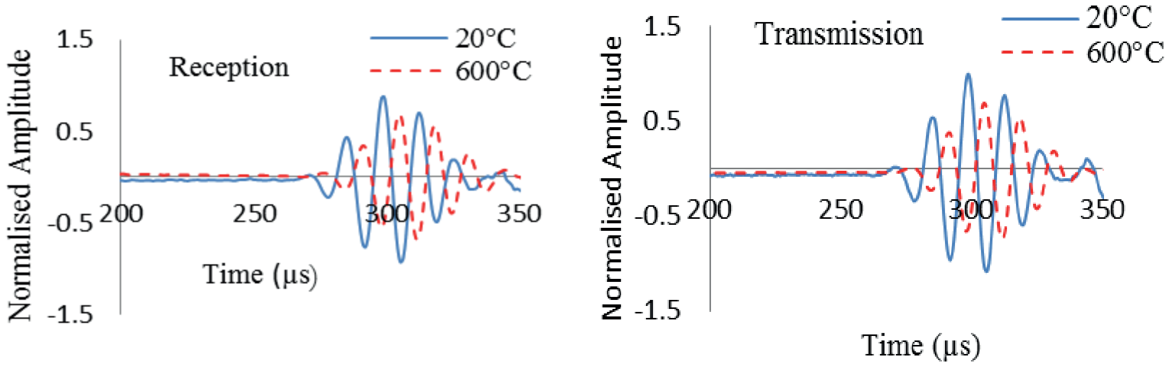

Figure 8: The measured reception and transmission transducer signals at 20°C and 600°C – the transducer is operational at 600°C, with an observable decrease in peak-to-peak amplitude

Figure 9 shows the manufactured transducer picture and average transmission and reception quality of lithium niobate LRUT transducer at up to 600°C. In the reception mode, a significant decrease can be observed between 200°C to 400°C, but from 450°C it starts to improve and at 600°C it reaches a similar performance in the reception quality as was observed at ambient temperatures. This behaviour could be due to the assembly procedure. The transmission quality is lower than the reception quality at ambient temperature, but between 250°C and 450°C the reception quality is lower than transmission quality. In the transmission mode the transducer is relatively stable between 20°C and 600°C.

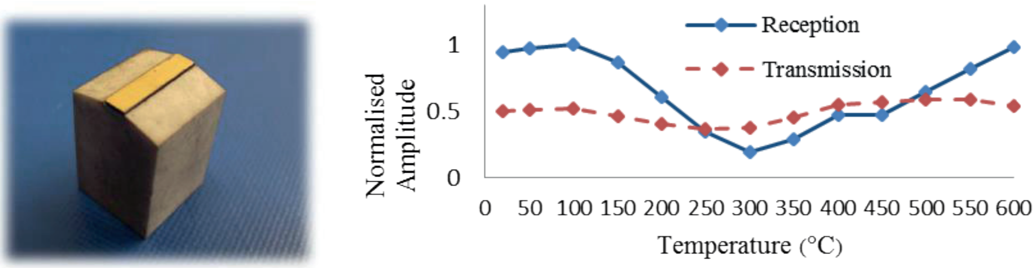

Figure 9: The lithium niobate shear-wave ultrasound transducer (left) and average transmission and reception quality of lithium niobate LRUT transducer at up to 600°C (right)

5 PULSER-RECEIVER ELECTRONICS FOR HIGH TEMPERATURE PA-TOFD

Each of the channels of the PA probe would have to be independently powered up by the pulser unit to control the direction of the wave front and define the focal point through high voltage signals time delays controlled by the microcontroller unit (µP). Switching of the transmit/receive mode (T/R) is also governed by the microcontroller, with the need of exhibiting high clock speed capabilities, especially considering the number of elements and frequency specifications of the probe. The reflected signals have to be amplified and filtered after being transmitted through the material in order to increase their signal-to-noise ratio (SNR). Finally, the function of the receiver is to employ the analogue-to-digital conversion (ADC) for microcontroller input.

The high-level block diagram of the pulser-receiver unit is being shown in Figure 10.

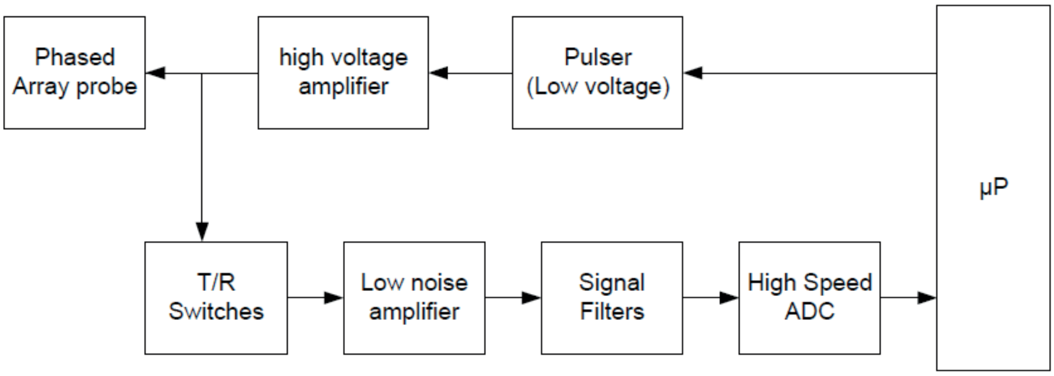

Figure 10: High level block diagram of the pulser-receiver unit.

The functions of the pulser-receiver unit were evaluated by powering a 5 MHz test probe in order to test the dimensions of an aluminium block, with known thickness of 38.5 mm. The results are demonstrated in Figure 11, with the time between the echo and the original pulse being 12.17 µs. As the sound propagation speed in aluminium is equal to 6320 m/s, it can be estimated that the thickness of the inspected material is equal to 38.45 mm.

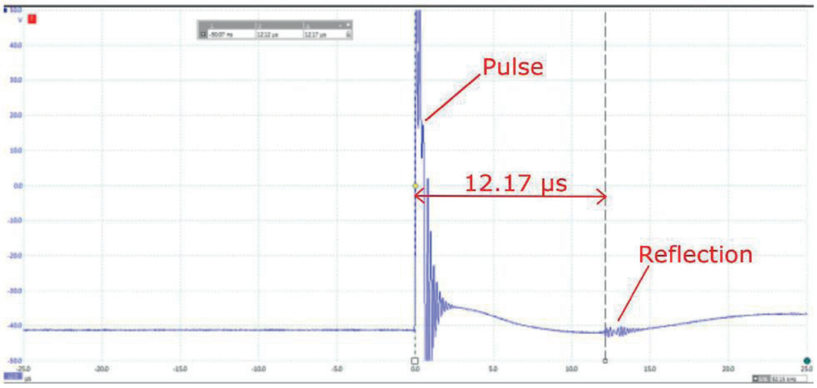

Figure 11: Aluminium block testing with the pulser-receiver unit and the test probe.

6 STRUCTURAL HEALTH MONITORING SYSTEMS

Plant operators are under increasing pressure to minimize the life cycle costs whilst maintaining availability targets and safety compliance. By defining the Probability of Failure (POF), the component with high risk level can be identified and it is possible through Risk- Based Inspection (RBI) assessment to set inspection and maintenance plans in order to obtain maximum value from the associated budgets.

The material properties of P91 steel had to be reviewed in order to generate a numerical model for: 1) prediction of the remaining life of each weld, 2) establishing POF curves for each weld, and 3) detection of the effectiveness of each risk factors and mitigation actions. RBI methodology can be used to manage the overall risk of a plant by focusing inspection efforts on the process equipment with the highest risk. In general, a large percent of the total unit risk is concentrated in a relatively small percent of the equipment items.

The calculation of risk involves the determination of a probability of failure combined with the consequence of failure. Failure in task is defined as loss of the capability of service of a component. SHM system analysis flowchart made for this work is given in Figure 12, with an example of POF calculation results done for this work are demonstrated in Figure 13.

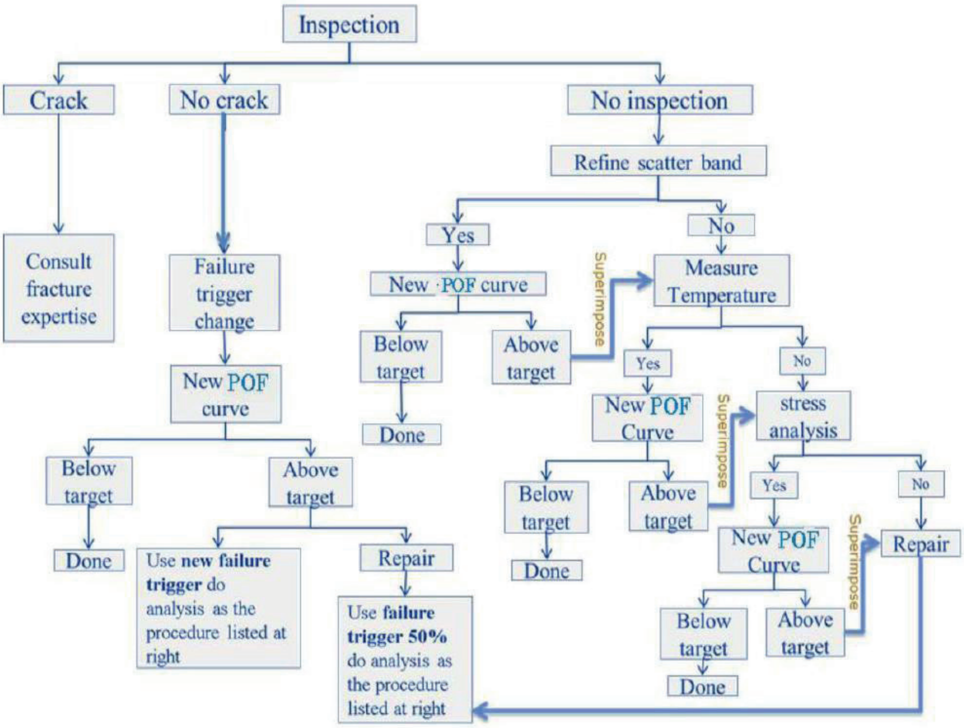

Figure 12: Structural Health Monitoring system analysis flowchart

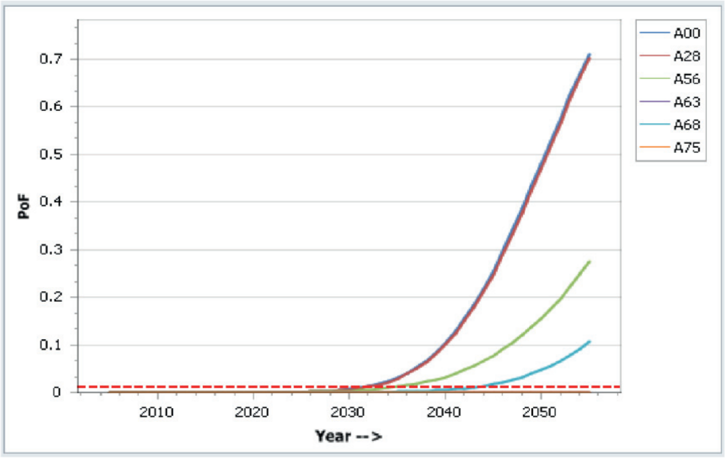

Figure 13: Example of POF-time curves for different welds

For the purposes of the demanding flaw detection task in the case of the UGW LRUT monitoring system, advanced signal processing techniques were developed and integrated within this work, using normalization, signal smoothing, correlation, baseline subtraction, feature extraction, selection and classification based on Support Vector Machines. For the training and validation of the UGW LRUT system, an extensive experimental investigation was carried out on different experimental setups. The results (Figure 14) show that the proposed method is able to effectively detect flaws under various temperature conditions and experimental scenarios.

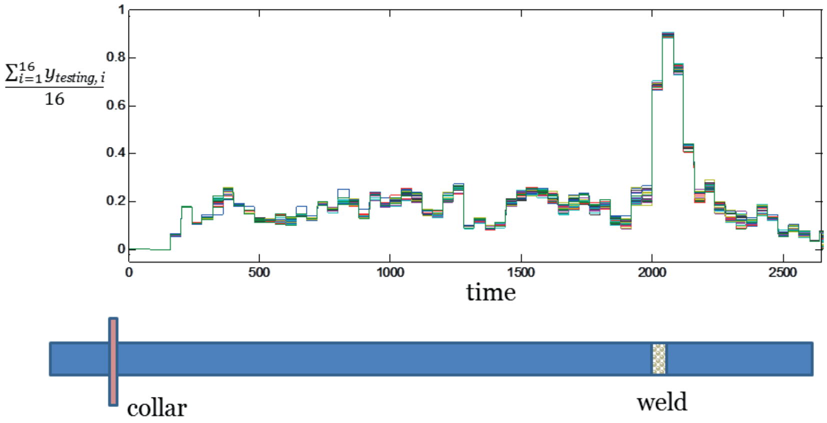

Figure 14: The output of the proposed signal processing module for a pipe at 250^{0}C with a 9% Cross Section Area (CSA) weld defect and a graph indicating the weld defect location in the pipe

The design of the high temperature stainless steel ring (collar) that carries the transducers is shown in Figure 15, together with a manufactured collar installed on a pipe.

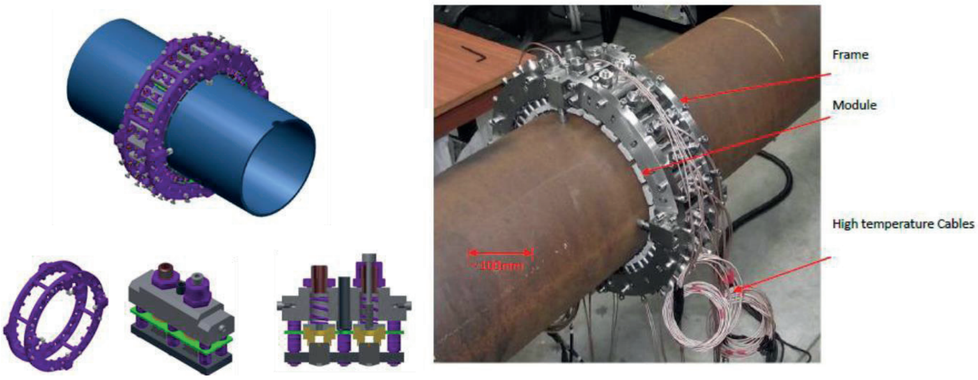

Figure 15: High temperature UGW LRUT monitoring system collar array

The integrated high temperature phased array TOFD system can be seen in Figure 16. The system consists of following key components: (a) high temperature PA probes using $GaPO_4$; (b) ruggedized PA pulser-receiver unit; (c) signal processing and visualisation software.

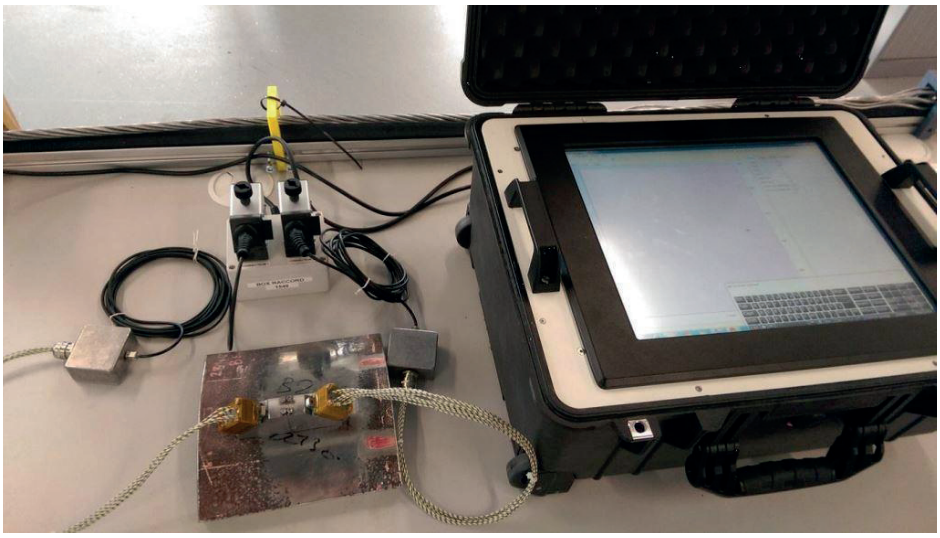

Figure 16: Integrated high temperature phased array TOFD SHM system

The PA probe using $GaPO_4$ was tested up to the target temperature of 580°C. For the coupling solution, SONO 1100 high temperature couplant was used. In Figure 17 one can see the manufactured PA probe using $GaPO_4$ coupled to a 25 mm thick P91 steel pipe section using the SONO 1100 high temperature couplant and placed in an oven. A thermocouple leading to a PC was used to ensure that the achieved temperature at the surface of the pipe test section is the correct one needed for measurement (580°C). After the pipe section was heated to the temperature of 580°C, the ultrasonic measurements with the manufactured PA probe were carried out to validate its performance at the target temperature of 580°C.

Figure 17: Phased array probe using $GaPO_4$ placed in an oven for characterisation at the target temperature of 580°C

In Figure 18 it is possible to see A-scans with multiple echoes from the back-wall of the pipe test section recorded at 580°C. The three echoes in the A-scan at 580°C are delayed compared to the echoes recorded at 25°C due to the change in velocity of P91 steel with rise in temperature.

Exposure to the temperature of 580°C was fatal for the elements 2 and 3 which responded with very much deteriorated ultrasonic signals.

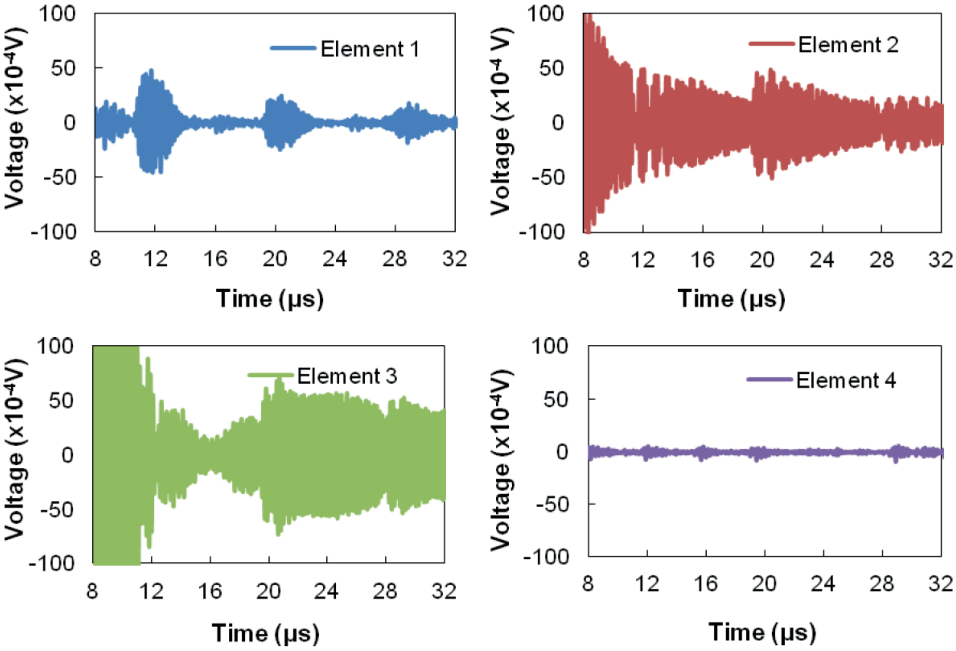

Figure 18: Multiple ultrasonic echoes at 580°C received on the 4-element $GaPO_4$ PA probe coupled to P91 steel pipe section using SONO 1100 high temperature couplant

On the other hand, the element 1 has survived the high temperature exposure and only a minor decrease in the amplitude value was observed from 25°C up to 580°C (Figure 19). This is more likely to be due to the adhesive rather than the element.

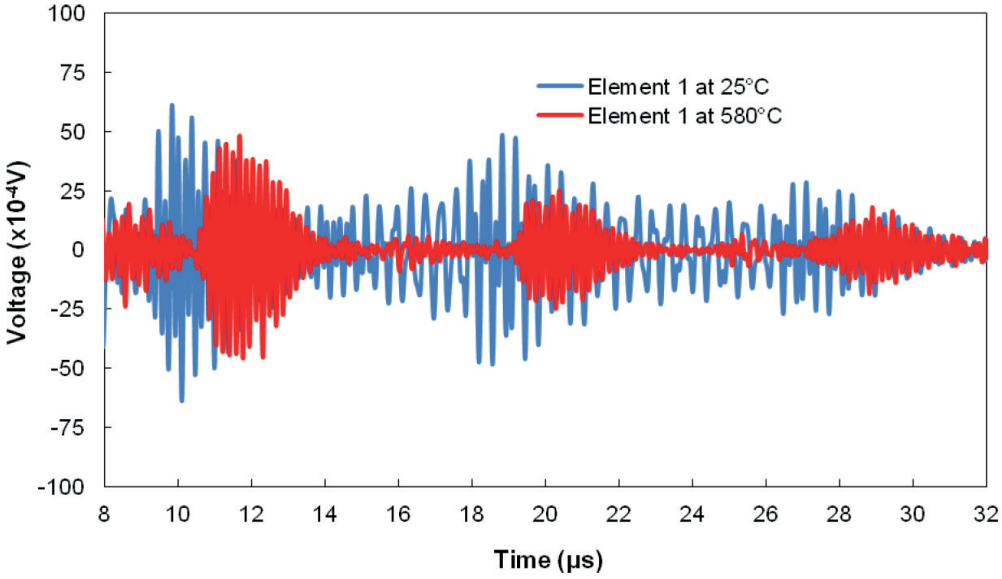

Figure 19: Compared multiple ultrasonic echoes at 25°C and 580°C received on the element 1 of the manufactured PA probe using $GaPO_4$ coupled to P91 steel pipe section using SONO 1100 high temperature couplant

7 CONCLUSIONS

Non-destructive testing of high temperature pipes and other critical components, as well as the estimation of their lifetime, is crucial for prevention of potentially catastrophic scenarios in power plants. This paper presents concepts and components of monitoring systems that will be permanently mounted on superheated pipes at the locations of known defects. The overall systems incorporate the use of ultrasonic phased array probes in time-of flight diffraction configuration, or an array of single element shear-wave ultrasound transducers, for the inspection of pipe welds. The usual problems with the acoustically active commercial piezoelectric materials (PZT ceramics) at high temperatures have been tried to be solved by using gallium orthophosphate and lithium niobate single crystals, which have been demonstrated as promising solutions even at temperatures up to 580 °C, at least for a reasonable period of monitoring time.

A pulser-receiver unit for the excitation of 16-element phased array probe has been shown, with functions validated through an example of the calculation of aluminium block depth. This unit also includes sensors for the monitoring of pipe temperature and calibration of pulsing/receiving signal parameters. The algorithm for the calculation of the Probability of Failure parameter, highly important in pipe lifetime estimation, has been developed and presented in this paper as well.

The expected benefits of such systems for high temperature pipe monitoring are:

- Increased safety in electrical production power plants;
- Elimination of catastrophic accidents from superheated steam pipe failures;
- Decrease of the required shut-down time for inspection purposes;
- Increase in confidence in the safety of thermal power and nuclear energy plants.

ACKNOWLEDGMENTS

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