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Introduction

This article investigates the use of a new type of wireless ultrasonic sensor for monitoring the thickness of equipment while on or offline. This is a case study of a CO_2 absorber tower in a remote location. The tower is vulnerable to runaway corrosion events. During these events the corrosion rates can be high enough to threaten the integrity of the vessel. To manage this risk, regular thickness readings are taken to confirm remaining wall thickness and, if necessary, provide adequate time for corrective measures to be taken. Inductosense ultrasonic sensor technology was selected for evaluation, which allows non-specialist plant operations personnel to measure wall thickness without the need for contracting specialists. The system is made up of permanently adhered sensors and a hand-held data collector. The sensors are inductively coupled to the data collector, allowing the ultrasonic measurements to be taken wirelessly.

Fifty sensors were installed on a section of a CO_2 absorber while operating. During the one-year proof of concept period, all sensors functioned and reported thicknesses. Manual nondestructive testing (NDT) and battery-powered wireless monitoring systems were used to validate the performance of the inductively coupled sensors. The inductively coupled system showed advantages in cost and accuracy.

Case Study

This article reports on a trial of three different NDT technologies carried out on a CO_2 absorber tower in a live production environment. The tower being monitored is in a remote desert area of Central Australia where access is challenging in harsh conditions. Its function is to reduce CO_2 in the incoming hydrocarbon gas stream from 20% to 4%. The tower was constructed in 1984 of carbon steel, measuring 20m (65' 7.4") high, 3.0m (9' 10") in diameter and 70mm (2.8") thick, operating at 6800kPa (986 psi) and 100°C (212°F).

CO_2 is removed using the UOP Benfield process which uses a recirculated hot potassium carbonate solution. Internal corrosion of the carbon steel tower is prevented through passivation treatments during start-up, and through the continual wetting of the tower walls by the potassium carbonate solution. Should the solution be prevented from contacting the vessel shell, then rapid corrosion can occur. An operating history of 36 years shows long periods of low corrosion activity, with rates as low as 0.02mm per year (0.0008 mpy) interspersed with corrosion events of short duration but high severity, where corrosion rates as high as 3mm per month (1.44 mpy) have been measured. The cause of these events is not the subject of this article but have been many and varied, with the common theme of poor (tower) wall wetting by the potassium carbonate solution.

Leading indicators, such as integrity operating windows, have been successfully used to manage solution chemistry, process parameters, and contaminant levels. Along with corrosion probes, they can also provide an indication of the "health" of the system. Extensive manual ultrasonic thickness testing supports these leading indicators and provides confirmation of tower integrity. Ultrasonic testing is an important direct measure of tower integrity, and due to the potentially high corrosion rates, it is conducted bi-monthly to allow corrective measures to be taken. The full circumference of the tower is monitored, adjacent to an internal packed bed near the top of the tower covering an area of 65m^2, 14m from grade. Studies and history have shown this is where the corrosion is active. As would be expected on a tower of this size, there is no direct access, therefore measurements are taken via rope access at significant cost. This ongoing expense drove the need to find an alternative means of measuring the thickness of the tower shell. The inductively coupled thickness monitoring patches/sensors provide one possible low-cost solution.

Trial Objective

The ongoing cost of taking manual measurements via rope access is high; two operators are required due to safety protocols, and working from ropes can be a relatively slow process. There is also a trade-off with accuracy. While great care is taken, the added complexity of taking ultrasonic readings manually from ropes, the high ambient and vessel temperatures, and the variable surface conditions of the tower shell all result in a variance in readings from month to month.

The tower operates at 100°C, and any hardware being used to take measurements must operate reliably at this temperature. In addition, the facility is sited in a remote desert region where access is limited. Day time temperatures reach 45°C regularly, dust is prevalent, and UV levels are extreme. Therefore, any hardware used for inspections must be robust and demonstrate reliability under these conditions.

These specific challenges lead to four assessment categories:

1. Cost
2. Accuracy
3. Reliability
4. Simplicity

Inductively Coupled System Overview

The wireless and nondestructive (WAND) system was initially developed by Zhong et al[1]. It uses inductive coupling to excite a wireless, battery-free ultrasonic sensor. The sensor is permanently bonded to the structure as illustrated in **Figure 1(a)**. The

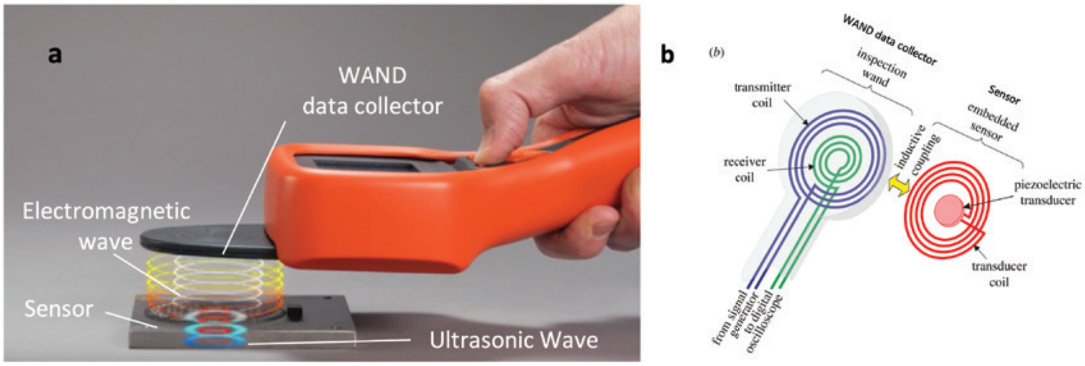


Figure 1. (a) Operation of WAND system, and (b) details of the inductive coupling between the WAND data collector and ultrasonic thickness sensor.

Figure 2. (a) Overview of sensors installed on the CO_2 absorber, (b) Magnet installation methods, and (c) Sensor protective coating.

inductive coupling is achieved using a three-coil network. One coil, termed the transducer coil, is connected to the piezoelectric transducer. The other two coils, called the transmitting and receiving coils, are contained within the WAND data collector and are connected to the outputs and inputs of the ultrasonic instrumentation as illustrated in **Figure 1(b)**. When the WAND data collector is held in close proximity to the sensor, electrical signals are transferred between the three coils and ultrasonic measurements are recorded from the sensors.

Compared to conventional manual ultrasonic testing, the system enables fast contactless measurements (each reading taking a fraction of a second), with a separation distance between the WAND data collector and sensor in the order of tens of millimeters. In a previous study Zhong et al. showed the system can be used to generate both bulk and guided waves enabling a range of different inspections[1]. The system has also been successfully used to monitor the curing process and detect damage in composite materials[2], to monitor the internal corrosion of pipework under composite wrap repairs[3], and to monitor tidal corrosion on the inside of a wind turbine monopile[4]. The sensors include an RFID tag that enables readings to be attributed directly to an operator and sensor at acquisition, a key advantage over manual ultrasonic testing methods.

Inductively Coupled System Installation and Sensor Measurement

Sensors were installed at 50 locations distributed evenly over a section of the tower. They were installed using a high temperature adhesive temporarily secured with a magnetic clamp, then finally protected from the environment with an epoxy coating (**Figures 2a**, **b** and **c**, respectively). The installation of all 50 sensors took three personnel three days to complete and was carried out while the vessel was in service.

Readings from the installed sensors were taken once every two months with on-site personnel. The plots in **Figure 3**, show the ultrasonic A-scans recorded from a sensor at location BI31 and its thickness plot over the year of recorded data. A-scans from the system are clear and remain consistent over the trial period. From this, it can clearly be seen that the quality of ultrasonic signal is maintained and the wall-loss over the period is detected. In this case the thickness was extracted from the peak arrival time.

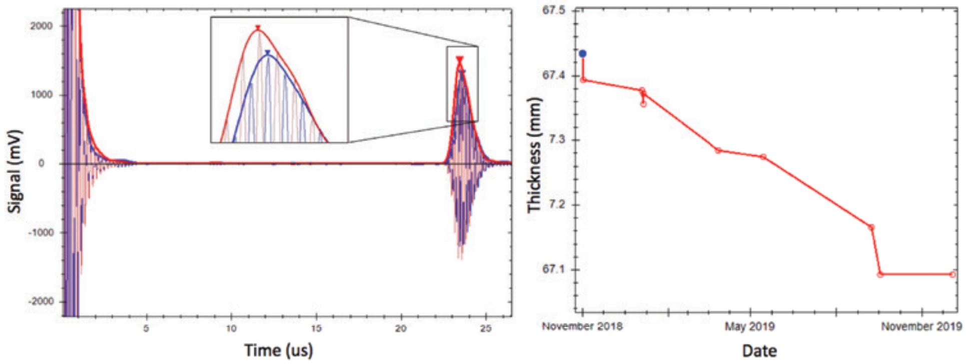
As the sensors are permanently installed and the calibration parameters such as ultrasonic velocity are associated with an RFID mounted next to the sensor, the system is able to provide repeatable, high quality data consequently leading to corrosion rate estimation whose accuracy will be discussed later.

Comparison of Measurement Techniques

There are three methods of thickness measurement employed on the tower:

- Manual ultrasonic thickness testing (UT) by rope access, a total grid of 6500 readings
- Semi permanently fixed wireless thickness (WT), testing probes 4 off
- Inductively coupled (IC) thickness testing patches, sensors 50 off

As previously discussed, the area at risk of corrosion is near the top of the tower, a region covering the full circumference of the tower over a height of 6.5m, 65m^2 in total. This area was divided into 100mm square grids which provides guidance to the NDT technicians and allows comparison of results between surveys. This grid is monitored bi-monthly via rope access with standard handheld ultrasonic probes capturing a single result at the center of each 100mm grid square. This is the primary means of



(a) (b)

Figure 3. (a) A-scan from a sensor (location BI31) showing final reading in red, and initial reading blue. The waveform and envelope are plotted. A zoom in on the peaks is included. (b) Thickness trend over one-year period for the BI31 sensor.

monitoring wall thickness and confirming tower integrity. It is important to note that there will be some variability between surveys as the NDT technician has to manually judge the centre of each square.

Four wireless thickness (WT) testing probes are installed on the vessel, within the gridded area, in grid squares that have previously shown active corrosion. These probes have the advantage of being permanently mounted and, hence provide data from an exact location with a record (reading every 12 hours) of wall thickness readily accessible via the plant digital control system (DCS).

The 50 inductive sensors, IC, were attached to a section of this gridded area in December 2018 at a separation of 500mm to give an even spread around the full circumference. They were read at the same frequency as the manual ultrasonic rope access surveys. An overview of these installations and the measurement grid can be seen in **Figure 5(a)**.

The fixed WT probes give two readings per day which provide a semi-continuous trace. To provide a direct comparison between the three approaches, only the results recorded on the dates of the other surveys were used. In all cases the selected measurement points are close to each other, but due to the potentially highly localized nature of the internal corrosion, it may show different values.

The tables below show the results used in the comparison. All thickness measurements are in mm, corrosion rates are in mm per year, and the locations shown refer to the grid reference on the vessel shell, which gives an indication of how close measurement locations are to each other.

Table 1. Inductosense, IC Readings

		Inductosense			
		Location 1 BM6	Location 2 BM26	Location 3 BM46	Location 4 BM76
Date	28-03-19	70.30	67.45	68.80	72.06
	15-05-19	70.35	67.56	68.85	72.11
	08-09-19	70.30	67.35	68.28	71.96
	08-09-19	70.40	67.40	68.30	72.00
	17-09-19	70.25	67.35	68.33	71.96
	04-12-19	70.40	67.25	68.28	71.90
	Max	70.4	67.56	68.85	72.11
	Min	70.25	67.25	68.28	71.9
	Variance	0.15	0.31	0.57	0.21
	Std dev	0.06	0.10	0.25	0.07
	Corr Rate	-0.15	0.29	0.76	0.23

Table 2. Fixed Probe, WT Results

		Fixed Probe			
		Location 1 BM3	Location 2 BM28	Location 3 BM53	Location 4 BM78
Date	28-03-19	73.19	67.89	70.26	72.96
	15-05-19	73.20	67.80	70.22	72.93
	08-09-19	73.17	67.80	70.10	72.83
	17-09-19	73.17	67.80	70.12	72.87
	04-12-19		67.59	70.05	72.79
	Max	73.2	67.89	70.26	72.96
	Min	73.17	67.59	70.05	72.79
	Variance	0.03	0.3	0.21	0.17
	Std dev	0.01	0.10	0.08	0.06
	Corr Rate	0.03	0.44	0.31	0.25

Table 3. Manual Ultrasonic, UT Readings

		Manual UT			
		Location 1 BM2	Location 2 BM27	Location 3 BM53	Location 4 BM76
Date	27-03-19	70.9	68.5	71.9	73.7
	22-05-19	72.4	66.8	71.5	73.9
	25-07-19	72.1	68.2	72.3	74.5
	18-09-19	72.7	67.2	71.8	73.4
	14-11-19	71.7	68.7	71.6	73.8
	Max	72.7	68.7	72.3	74.5
	Min	70.9	66.8	71.5	73.4
	Variance	1.8	1.9	0.8	1.1
	Std dev	0.62	0.75	0.28	0.36
	Corr Rate	-1.26	-0.31	0.47	-0.16

Trial Assessment

Clearly each technology is capable of measuring wall thickness and tracking changes, which is the core requirement of monitoring. This section considers how each approach performs against the trial assessment criteria:

- Cost
- Accuracy
- Reliability
- Simplicity

Table 4. Cost Comparison. (Note set-up costs were normalized to the cost of the IC Probes.)

	Set-up Costs		Ongoing Activities		
	System Setup	*Probe/Sensor Purchase & Installation*	*Measurement*	*Reporting*	*Maintenance*
50 Inductosense, IC	1	1	0.5 Hr	0	Nil
4 Fixed Probes, WT	1.25	0.8	0	0	Annual remove, clean re-install 3-5 Year battery replacement
3300 Manual, UT	1	0	48 Hrs	2 Hrs	2 yearly clean off UT grease

Cost

The system setup costs for the three techniques is captured in **Table 4** and normalized to the cost of the inductively coupled sensors. All three techniques used the grid stencilled onto the outside of the tower. There are additional expense incurred by the fixed probes in setting up a wireless gateway and the DCS. The fixed WT probes required a Wi-Fi network in order to communicate to a dedicated server, thus adding complexity to the initial setup of the data capture and reporting process with company fire walls and data security protocols needing to be managed. This is resulted in the slightly higher set-up cost for the fixed probes.

The purchase and installation costs of the inductive probes were slightly higher than the fixed probes. However, there are 50 inductive sensors compared to four fixed WT probes. Realistically, installing and commissioning the inductive sensors and the fixed probes cost the same. The inductive sensors have an advantage in that additional sensors can be added at a fraction of the original set-up cost.

It is in collecting and managing the thickness data where the cost differences are noticeable. Considerable hours are spent gathering manual UT readings, collating data, and producing reports, compared to just 30 minutes for the inductive sensors. Once familiar with the wand, 50 sensors were being read within 20 minutes, less than 30 seconds per sensor. The fixed WT probes record automatically and take daily readings at no cost. This is important where trend building is required; an accurate trend can be built quickly and continuously with no resources required at site. The advantages of both the fixed WT probes and the IC sensors over manual UT is data security, auditability of readings, and the ready access to data histories. For manual readings, reports are written at additional cost, and over time it is difficult to keep and display histories, typically requiring ad-hoc solutions or third-party software.

With manual UT there is some maintenance required to clean off the UT measurement paste every two years to prevent build-up and measurement errors. This is costly due to access restrictions as it requires a crane to execute. A change in couplant better able to manage the high vessel surface temperatures is being trialed to see if the cleaning cycles can be extended.

Some of the fixed WT probes have required re-seating every 1 to 2 years as they lose contact with the vessel shell. The cause for this is under investigation and may be due to temperature cycling of the tower, or possibly from being knocked by the rope access technicians during their UT surveys. The fixed WT probes will also require battery replacement after approximately 3 to 5 years, this replacement date can be managed to a certain extent by changing the number of readings taken in a 24-hour period. To date the inductive sensors have required no maintenance.

In comparing the running costs of the three approaches, the cost of manual UT grows very quickly over time. This is due to the time taken to capture the large number of thickness readings, while the relative cost difference between the IC sensors and the fixed WT probes is minor.

Accuracy

To compare the accuracy across the three measurement techniques, three measures were used:

- Range, the difference between maximum and minimum readings over the measurement period
- The standard deviation
- The measured corrosion rate over the survey period

The values of these three metrics are shown for each thickness monitoring approach in **Tables 1-3**. What is immediately obvious is the commonality between the IC probes and the fixed WT probes, and the difference in results between these two techniques and the manual readings. In comparing the fixed and IC probes, the range between the max and min values is comparable and in both cases is similar to the corrosion loss suggesting the measured range is due to actual material loss, not reading inaccuracies. Further, the corrosion rates, while not the same, are within the same order of magnitude across all readings. This is consistent with what is expected from the CO_2 absorber, as experience has shown the corrosion within the tower is not uniform. The standard deviation shows similarly robust performance for the two permanently installed solutions.

When the manual UT readings are examined, the difficulties in getting repeatable readings between surveys are clearly displayed. The NDT technicians are responsible for measuring over 6000 points. This takes several days in what are non-ideal conditions considering the environmental extremes of a desert region. Readings are taken at the centre of a 100mm square. While this

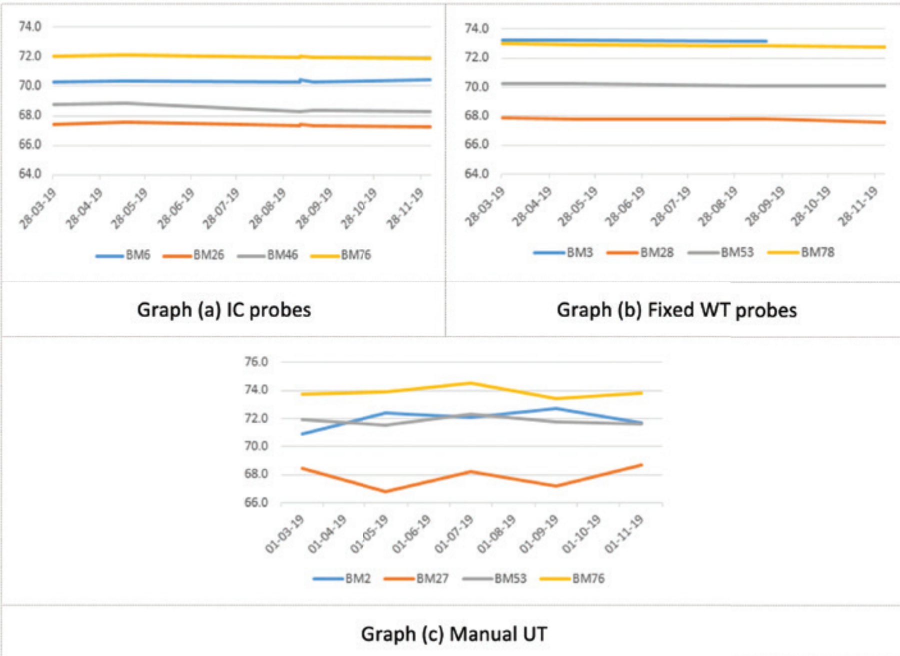


Figure 4. Showing the measured thicknesses. All readings are in mm and the Y-axis scales adjusted to show a 10mm thickness range for comparison purposes. Locations shown refer to the grid reference around the vessel circumference.

provides a "similar" location suitable for quickly scanning large areas and proves the vessel as "fit for service", the accuracy is not comparable to a probe installed at a fixed location.

Inspection is carried out on live plants that cannot be routinely cleaned down. This results in a build-up of couplant over time. This along with the presence of dust and surface imperfections on the vessel adversely affect the accuracy of manual readings, which is not an issue for the fixed WT probe or IC sensor. These factors lead to human errors with manual UT, even resulting in occasional measurements of the wrong grid square.

The measured corrosion rate is another variable which unsurprisingly demonstrates the benefits of a fixed probe/sensor. The improved accuracy and reduced range between successive readings allow an accurate corrosion rate to be established, something that is not possible with manual readings. **Figure 4** displays the readings taken and clearly shows corrosion loss over time for the fixed probes and sensors, whereas the variability of the manual readings hides any material loss.

Reliability

The reliability of manual UT inspection is well known; the technology has been available for a considerable time. The fixed WT probes are a relatively new application and have also performed well. First installed in 2017, they have been recording readings twice per day for over two years and, apart from an annual re-seat for some probes, they have recorded faultlessly over that time. There have been no battery issues, software faults, or loss of signal.

The IC system consists of two parts. The IC sensors were attached to the vessel in early December 2018, and the first readings recorded on December 4, 2018. At the time of installation, the sensors, including their RFID tags, were coated with an epoxy resin. The vessel runs between 100 and 110°C since the sensors are attached to its external shell, exposed to full sun and the elements. The climate is arid desert with an average annual rainfall of 205mm; daytime temperatures can exceed 45°C in the shade. Dust storms are not common but do occur. As noted, the vessel is monitored with manual UT via rope access by technicians who no doubt have kicked, or at least brushed and trodden, on the sensors. A visual inspection at the end of the trial showed them to be covered in NDT grease, but otherwise undamaged (**Figure 5(b)**). The epoxy coating has shown no sign of damage or time-dependent degradation and continues to provide protection to the IC sensors and RFID tag.

The sensors have been read every 2 to 3 months over a period of 12 months with very little issue. A reconfiguration of the wand was completed in March 2019 to improve accuracy. One of the RFID tags failed after 10 months of operation, but the associated thickness sensor continues to function. The general state of the sensors can be seen in **Figure 5**.

The data collector WAND has performed without fault during the past 12 months. It is temperature sensitive, as would be expected of most electronic devices, having a high temperature cut-out at 60°C. This was triggered on one survey where the ambient temperature was above 45°C. This combined with the vessel shell temperature of 100°C caused the WAND to overheat and shut down. However, the wand was not allowed to cool between readings to test its durability. Once it had cooled, the WAND continued to function reliably demonstrating its robustness. Later surveys under similar conditions were controlled to minimize the time the wand spent against the shell of the vessel and to allow it to cool between readings. This, in turn, added minimal time to collecting the survey results across the 50 sensors.

Apart from the one RFID failure, the IC sensors, wand, and software have operated reliably.

Figure 5. Photographs of sensors after months in service on a "live" plant. (a) Overview of installed sensors and measurement grid with fixed WT probe visible. (b) Detail of sensor BQ11 showing high levels of couplant and poor surface state.

Simplicity

The facility used for this trial is remote and fault finding can be difficult due to access restrictions. As such simple systems are preferred, dealing with complex software, network requirements, electronic equipment, training personnel and troubleshooting can be a significant challenge.

Installing the IC sensors was achieved via scaffolding. Setting up the database and software required support from the vendor; however, once set up the software and data collector WAND have been easy to use. Numerous personnel have taken readings with only a short 5-minute training demonstration required. There is some skill required in getting a timely reading and locating the wand correctly over the sensor, which does take some practice. For tracking purposes, a template was used to manually record when a reading was taken. The technicians taking the readings found it beneficial to track their progress to ensure no sensors were missed during a survey.

Discussion

The trial reported in this article has shown that the IC sensors can be used to take measurements in a harsh environment. The trial has highlighted the strengths and weaknesses of the currently deployed inspection methodologies.

Manual UT measurements are the most well-known and, as such, their performance is very well understood. Such measurements can offer excellent coverage allowing an overall picture of a vessel's condition to be determined. However, due to significant variability in measurements, the error bars in any thickness map made with manual UT are large. This means that although coverage is comprehensive, confidence is low and as such corrosion rates are difficult to measure and the time between inspections must be short. A surprising result from this trial has been the relatively high cost associated with manual inspections.

Fixed WT probe measurements offer excellent measurement performance, and when high frequency monitoring of a location is required are the optimum solution, providing real time corrosion rates. However, the cost of each measurement point is high, meaning that only a limited number can be deployed, and an overall picture of vessel integrity cannot be achieved.

The IC sensors investigated in this trial offer capabilities in between the other two methods. Sensors are cheap enough to be installed in sufficient bulk to assess vessel integrity and offer repeatable measurements to track corrosion rates. One feature worth noting here is that in this instance all data was processed using the simplest measurement possible—peak arrival time. It is likely that more advanced signal processing, for example using a 6dB drop may provide even better accuracy. In common with all permanently installed sensors, such developments can be readily applied to existing data increasing its value over time, which is a key advantage for operators.

Conclusion

This trial aimed to investigate the real-world performance of a new approach to permanently installed thickness monitoring. Fifty wireless battery-free ultrasonic thickness measurement patches were successfully installed in a difficult environment. All sensors are functional and reporting corrosion rates over a 12-month period. An average corrosion rate of 0.27 mm per year is being calculated from the obtained data. A comparison of three different approaches based on cost, accuracy, reliability, and simplicity has shown that, while all have specific benefits, this new sensor technology offers a unique set of advantages. Specifically, in a difficult to access harsh environment such as this trial was conducted in, it offers a useful new tool for assessing integrity. ■

For more information on this subject or the author, please email us at inquiries@inspectioneering.com.

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