USING ULTRASOUND MEASUREMENTS FOR REAL-TIME PROCESS CONTROL OF PIPELINES AND PROCESS EQUIPMENT SUBJECTED TO CORROSION AND/OR EROSION

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ABSTRACT

Corrosion and erosion remain two key issues in petroleum production. In the last few years, there has been an increasing demand for online process control where the rate of metal loss may be monitored. From an ultrasound perspective these challenges reduce to measuring the wall-thickness over time. By combining permanently installed sensors, low noise measurements and temperature compensation, lab experiments have shown that it is possible to detect changes in wall thickness on the sub-micrometer scale. The results suggest that ultrasound technology is well suited for real-time corrosion monitoring applications, and that it may be used for inhibitor control and optimization as well.

Keywords: Ultrasound, real-time monitoring, temperature compensation, high resolution

INTRODUCTION

Using ultrasound is a well-established approach in the non destructive testing community for measuring wall thickness and detecting defects. Recent electronics/hardware advances have made it possible to develop ultrasound modules which detect sub-micrometer changes in the wall-thickness. This paper investigates the possibilities of using permanently installed ultrasound modules based on the clamp concept (see Figure 1) for real-time corrosion/erosion monitoring systems [1], [4]. Even though [1] and [4] describes a system for subsea installation, this can easily

be extended to onshore installations as well. In order to achieve this, factors related to signal to noise ratio and temperature variations must be understood and optimized. By suppressing noise, one enhances the system's time response which tells us something about the time it takes to detect a change in wall thickness. The simple relation between the corrosion rate and the change in wall thickness makes it possible to estimate the annual corrosion rate based on consecutive wall thickness measurements.
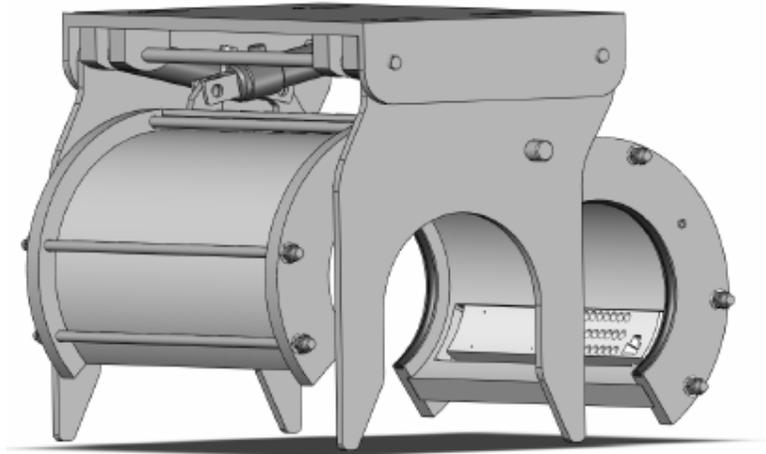
Figure 1 - Ultrasound instrumentation mounted on the inside of a protective mechanical clamp

This paper discusses two different experiments; one where a steel specimen is exposed to a corrosive environment and one where the specimen is exposed to temperature variations. Ultrasound measurements are performed on the specimen all along. The results from these experiments are integrated into a proof of concept web interface for real-time, temperature compensated thickness monitoring of the steel sample.

Relating Ultrasound Technology to ER and LPR Monitoring Techniques

The electrical resistance (ER) principle is based on exposing a specimen of the target material and measuring the increasing resistance as the specimen corrodes. Reported results suggest that it takes at least 15 minutes (0.26 hours) to detect a change with an annular corrosion rate of 0.1 mm/year [2] using this technology with the most sensitive probe. The time response highly depends on the lifetime of the ER-probe; if one wants high sensitivity, the lifetime of the probe decreases correspondingly.

The linear polarization resistance (LPR) principle is based on electrochemical techniques, and this is the most accurate method in use today for determining the corrosive environment. By combining LPR with electrochemical noise and harmonic distortion analysis, it is possible to measure the corrosion rate in 7 minutes [3]. One serious limitation is that it requires continuous conductive water phase. As for the ER probes, LPR probes also have a limited lifetime.

The noninvasive ultrasound approach described herein differs from employing LPR or ER probes in that it directly measures the corrosion rate on the pipeline. The thickness is given by simple pulse-echo measurements. By analyzing several consecutive traces, one obtains the corrosion rate. In addition ultrasound sensors have no theoretical upper lifetime-limit as it is not affected by the corrosive environment inside the pipeline. If one distributes a number of transducers around the pipeline as described in [1] it will be possible to extract information about localized corrosion; more sensors increase the probability of detecting localized attacks.

ACHIEVING RELIABLE CORROSION RATES

Minimizing noise and temperature effects are of vital importance in order to achieve sub-micrometer resolution for the thickness measurements. This section discusses the wall-thickness measurements, thermal effects and how to relate this to a reliable estimate of the corrosion-rate.

Signal Characteristics
The thickness is given by simple pulse-echo measurements, for which an example is shown in Figure 2. By analyzing several consecutive traces, one obtains the corrosion rate.
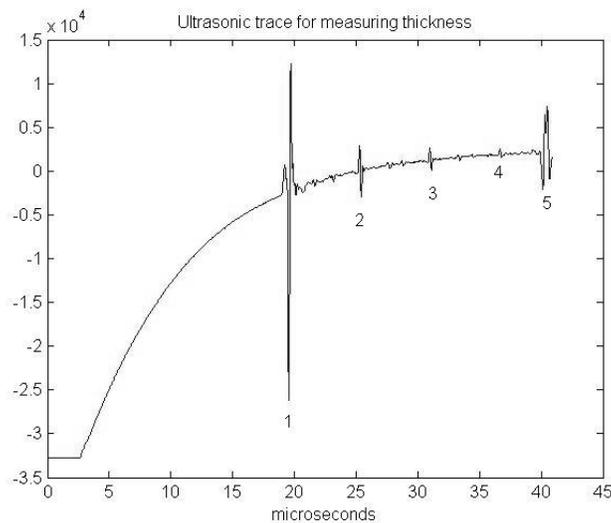

Figure 2 - A 5 MHz ultrasound trace.

Referring to Figure 2, the deflection at label 1 represents the first reflection from the outer wall, i.e. the transducer side of the steel plate. The labels 2, 3 and 4 represent reflections from the inner wall where the acoustic wave has propagated once, twice and three times back and forth in the steel respectively before moving back to the transducer. Label 5 represents the pulse which has traveled twice back and forth between the transducer and the outer wall. Since the time interval between label 1 and label 2 is the time it takes for the acoustic pulse to move once back and forth in the steel, this information is used to calculate the thickness, d, which is given by the following formula

$$d = c\frac{t}{2} \tag{1}$$

Here t denotes the time from label 1 to label 2 and c is the acoustic velocity in steel.

Temperature Variations
Using ultrasound wall thickness measurements in process control applications requires control of temperature variations, for which there are two relevant issues:

1. Thermal expansion of materials.
2. Thermal variations of sound speed.

Thermal expansion is often modeled by the linear thermal expansion coefficient which relates the change in temperature to the change in the material's dimensions by the following equation:

$$\alpha = \frac{1}{d_0} \frac{\Delta d}{T - T_0}$$

(2)

where α is measured in μm/(mK). Further d_0 is the length of the material at temperature T_0 and Δd is the thermal expansion. For carbon steel, $\alpha \in [10.8, 12.8]$ [7] for temperatures in the range 20-100 degrees Celsius. If one relates this to a pipe-wall of 15 mm, it corresponds to an expansion of 0.16-0.19 μm/K.

The speed of sound is given by the plane wave modulus, M, and the density, ρ, as

$$c(T) = \sqrt{\frac{M(T)}{\rho(T)}}$$

(3)

The plane wave modulus is in turn given by Young's modulus, E, and the Poisson's ratio, v, as

$$M(T) = kE(T)$$

(4)

where $k = \frac{1-v}{1-v-2v^2}$. Young's modulus will in turn depend on temperature, and earlier work [8] suggests that the E varies with temperature in a linear manner:

$$E(T) = E_0 + \beta(T - T_0)$$

(5)

The Poisson's ratio, and hence k, is assumed not to vary with temperature. Here E_0 is Young's modulus at T_0 degrees Celsius while β is a material-specific parameter. Due to the thermal expansion, the density will also be temperature-dependent. By using the fact that the total mass will be constant during the expansion the density can be expressed as:

$$\rho(T) = \frac{\rho_0}{(1 + \alpha(T - T_0))^3}$$

(6)

Here ρ_0 is the density at T_0 degrees Celsius. Plugging equation (4), (5) and (6) into equation (3) yields

$$c(T) = \sqrt{k(E_0 + \beta(T - T_0)) \frac{(1 + \alpha(T - T_0))^3}{\rho_0}}$$

(7)

By incorporating thermal effects equation (1) becomes:

$$d(T) = \hat{d}_0(1 + \alpha(T - T_0)) = c(T)\frac{t}{2}$$

(8)

Here t is a measured quantity and thus considered a constant. Inserting equation (7) into (8) and rearranging yields

$$\hat{d}_0 = \sqrt{k(E_0 + \beta(T - T_0)) \frac{(1 + \alpha(T - T_0))}{\rho_0}} \frac{t}{2}$$

(9)

and we have the temperature compensated wall thickness at temperature T_0.

Relating Thickness Measurements to a Constant Corrosion Rate
In the following, we take a statistical approach to calculating the corrosion rate. From each ultrasound measurement the thickness of the pipe wall is calculated. When the temperature compensated thickness calculations are plotted versus time, one obtains a dataset for which an example is illustrated in Figure 5. In order to calculate the corrosion rate from such a dataset, we assume that the specimen corrodes with a constant rate in a certain time interval. Thus one can approximate the dataset as a linear function:

$$y = at + b$$

(10)

where y is the thickness given at time t, while a and b are constants. The constant a is the most interesting as it gives the estimated corrosion. By defining each of the N data points in the dataset as $(t_i, y_i), i = 1, 2, ...N,$ one can associate an error ε to each measurement:

$$\varepsilon_i = y_i - (at_i + b)$$

(11)

It is assumed that the error follows a Gaussian distribution. The next step is to employ a least squares technique (see e.g. [6]) to calculate the constants a and b which minimizes the error sum, ES:

$$ES = \sum_{i=1}^{N}(y_i - at_i - b)^2$$

(12)

The uncertainty related to the estimation is calculated by the standard deviation. This is a measure of how much the thickness measurements deviates from the estimated linear function, and is given by

$$\sigma = \sqrt{\frac{1}{N-p}\sum_{i=1}^{N}(y_i - y(t_i))^2}$$

(13)

The parameter p reflects the number of parameters which is estimated. Herein p equals 2. The less standard deviation, the fewer measurements and less time it takes to calculate a trustworthy corrosion rate. By computing a *100(1-γ)%* confidence interval for the estimated corrosion rate $\hat{a}$ one can determine the reliability of the results. The confidence interval is given by [5]

$$\hat{a} \pm t_{\frac{\gamma}{2},N-2}\sqrt{\frac{s_y^2 - \hat{a}^2 s_t^2}{(N-2)s_t^2}}$$

(14)

where $t_{\frac{\gamma}{2},N-2}$ follows the Student's t-distribution with *N - 2* degrees of freedom and

$$s_t^2 = \frac{1}{N-1}\sum_{i=1}^{N}(t_i - \overline{t})^2, s_y^2 = \frac{1}{N-1}\sum_{i=1}^{N}(y_i - \overline{y})^2$$

(15)

Further, $\overline{t}$ and $\overline{y}$ denote the average of *t* and *y* respectively.

Note that when discussing sub micrometer accuracy, it is the relative thickness differences which are discussed, i.e. the relative change in thickness from one measurement to the next. The absolute thickness will in general have an uncertainty of a few hundred micrometers. This bias will only affect the parameter *b* in equation (10) but it will have no impact on the estimated corrosion rate denoted by the parameter a.

EXPERIMENTAL SETUP

This section describes the two types of experiments which have been performed during this work.

Temperature Experiment
A carbon steel specimen is immersed in glycol together with a transducer in a vessel. The specimen works as a measuring object. First the vessel, including the specimen and the transducer, is put into the freezer. When the temperature has reached about -10 degrees Celsius, the vessel is placed in

an oven and heated to about 70 degrees Celsius after which the oven is turned off. Ultrasound as well as temperature measurements are continuously performed during the experiment.

Corrosion Experiment

The experimental setup consists of a test cell immersed in a corrosive liquid. The test cell has an end cap made of carbon steel which also works as a measuring object. Further, the test cell is filled with glycol in order to minimize corrosion on the "transducer-side" of the steel block. An immersion transducer is placed in the test cell separated with 15 mm standoff from the carbon steel. The glycol is then functioning as acoustic coupling medium between the transducer and the carbon steel. As the test cell lies in corrosive liquid, the steel block will gradually corrode. The corrosiveness is modified by changing one of the two parameters pH or salinity. In order to reduce deposits on the specimen, a pump ensures circulation.

In addition, a reference steel specimen with known thickness and equivalent material parameters is used for temperature compensation. This is a practical alternative to use when the material parameters of the temperature model in the previous section are unknown. The reference specimen is not affected by the corrosive liquid but it is affected by the same temperature variations as the corroding specimen. Figure 3 illustrates the experimental setup.
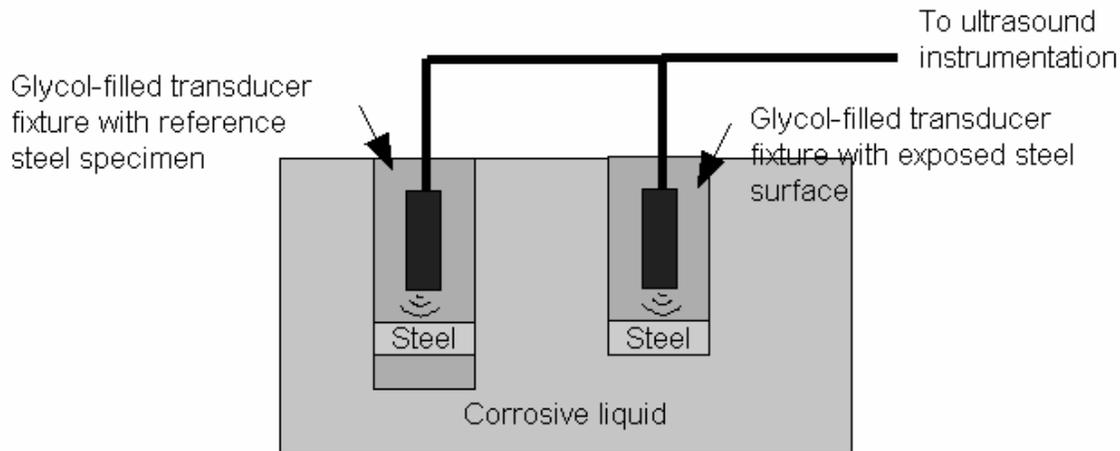

Figure 3 - Experimental setup for the corrosion experiment.

RESULTS AND DISCUSSION

This section presents the results from the temperature experiment as well from the corrosion experiment.

Temperature Experiment

In this experiment, equation (9) is employed to achieve temperature compensation. The following material parameters are inserted into the model:

- Young's modulus: E_0 = 210 GPa
- Density: ρ_0 = 7872 kg/m^3
- Temperature: T_0 = 25 degrees Celsius
- Poisson's ratio: v = 0.295
- Change in E with temperature: β = - 47.7 MPa/K
- Linear thermal expansion coefficient: α = 12.8 μm/(mK)

Precise data for the material parameter β at temperatures from 0 – 100 degrees Celsius is to a large extent lacking, but the chosen value is in accordance with earlier work [8].
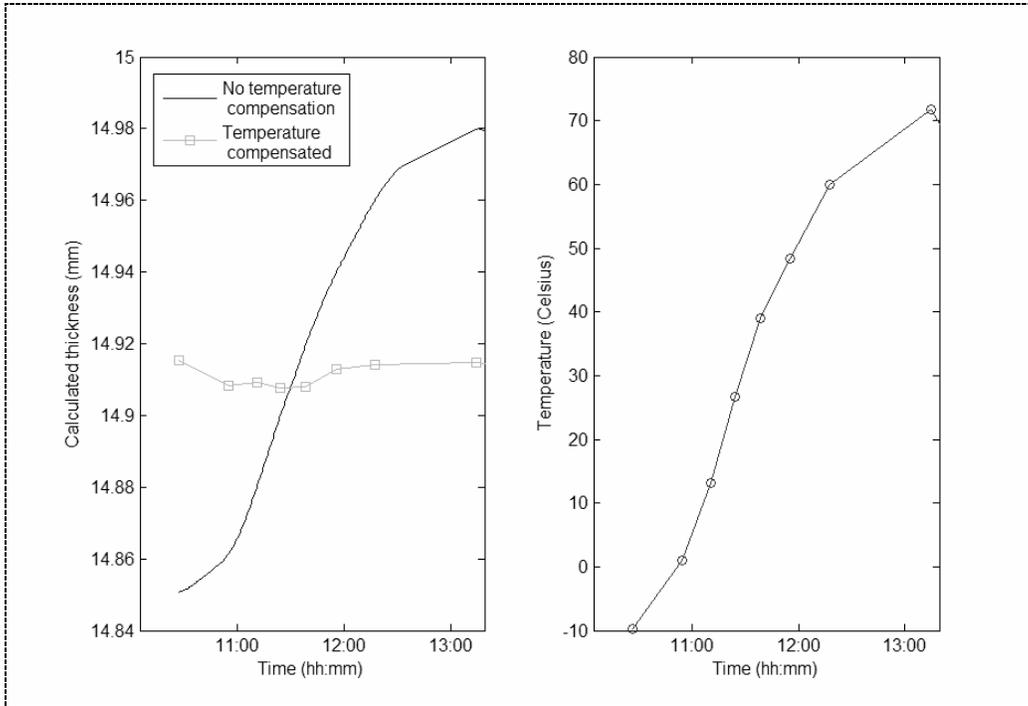
Figure 4 – Measured thickness with and without temperature compensation to the left. The corresponding temperature graph to the right.

If one compares the graphs of the uncompensated thickness measurements and the temperatures in Figure 4, it is clear that the temperature and thickness variations are nearly linear. This suggests that equation (9) (at least with some materials) may be approximated by a first order Taylor expansion, an approach suitable if one wants to reduce the calculation complexity.

By inserting the temperature data as well as the data from the uncompensated thickness measurements into equation (9), the temperature variations are reduced significantly (about 94 %). This is seen by comparing the two graphs in the left plot of Figure 4.

As the parameter β is below zero, it is clear from equations (3)-(5) that both the thermal expansion as well as the change in Young's modulus will bias the calculated thickness in the same direction with no temperature compensation; the calculated thickness will increase with increasing temperature. Only the density will work in the opposite direction, but as seen in Figure 4 the former two effects will affect the calculated thickness the most.

Corrosion Experiment
By employing the equations (10)-(15), the annual corrosion rate $\hat{\alpha}$ is estimated together with its confidence interval. Herein, a 95% confidence level is used. There are 10 seconds between each measurement. Thus N measurements correspond to 10N seconds. As expected, the confidence to the results improves as the number of incorporated measurements increases. The pH is 6.5 for both the high and medium corrosion rate experiments; only the salinity is reduced in the medium rate case.

A dataset for this experiment is shown in Figure 5. The corresponding results are presented in Table 1.
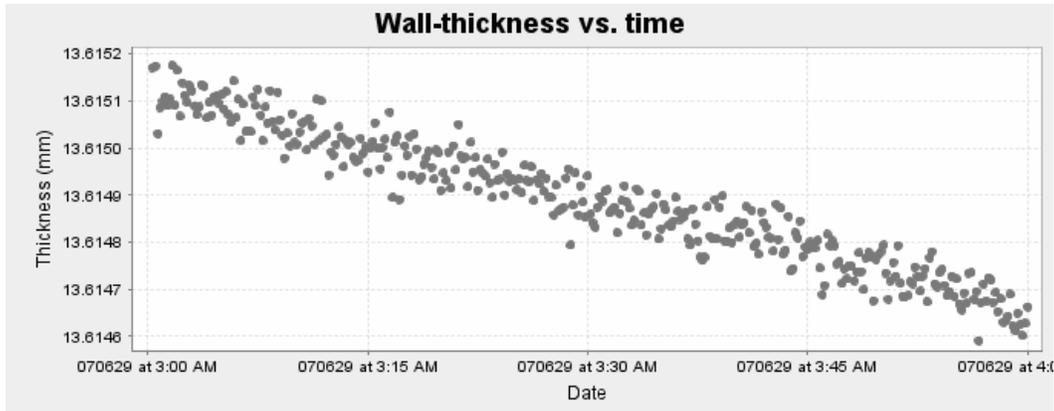
Figure 5 - A typical dataset from the corrosion experiment. Here the steel specimen has corroded about 0.5 micron in one hour.
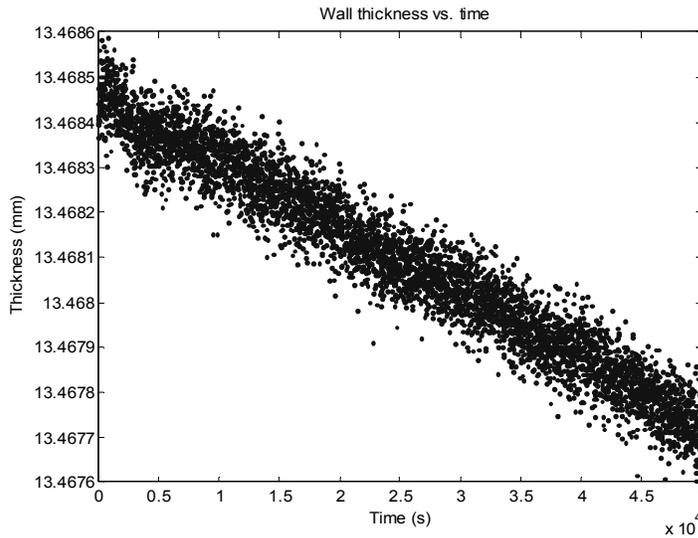
Table 1 - Results from the high rate corrosion experiment. The results show the estimated corrosion rates and the corresponding 95% confidence interval based on 10, 20, 50, 100 and 350 measurements.

Number of measurements	$N = 10$	$N = 20$	$N = 50$	$N = 100$	$N = 350$
Corresponding time	1min 40s	3min 20s	8min 20s	16min 40s	58min 20s
$t_{0.025, N-2}$	1.860	1.734	1.676	1.660	1.645
$\hat{a}$ (mm/year)	-3.7	2.16	3.84	4.62	4.01
Confidence interval (mm/year)	±27.73	±7.70	±1.78	±0.660	±0.106

It is evident from the table above that the confidence interval decreases as more measurements are incorporated into the calculations. After 8min 20s the 95% confidence interval is 4.62 ± 0.660 mm/year = [3.96, 5.25] mm/year, i.e. one knows with 95% certainty that the corrosion rate lies within that interval. After an hour the 95% confidence interval has changed to 4.01 ± 0.106 mm/year = [3.90, 4.16] mm/year. By employing even more measurements, the confidence interval will decrease further.

Medium corrosion rate
A dataset for this experiment is shown in Figure 6. The corresponding results are presented in Table 2.

Figure 6 - The corrosion rate in this experiment is -0.464 mm/year ± 0.004 mm/year. This is based on the 4000 first measurements.

Table 2 - Results from medium rate corrosion experiment. The results show the estimated corrosion rates and the corresponding 95% confidence interval based on 100, 350, 1000, 2000 and 4000 number of measurements.

Number of measurements	N = 100	N = 350	N = 1000	N = 2000	N = 4000
Corresponding time	16min 40s	58min 20s	2h 46min	5h 32min	11h 4min
$t_{0.025,N-2}$	1.660	1.645	1.645	1.645	1.645
$\hat{a}$ (mm/year)	0.596	0.674	0.452	0.468	0.464
Confidence interval (mm/year)	±0.897	±0.135	±0.029	±0.010	±0.004

After 2h 46min the 95% confidence interval is 0.452 ± 0.029 mm/year = [0.432, 0.481] mm/year. After 11h 4min hour the 95% confidence interval has changed to 0.464 ± 0.004 mm/year = [0.460, 0.468] mm/year.

Effect of Temperature Compensation During Corrosion of the Test Specimen

The dataset in Figure 7 is recorded in the lab over a period of 42 hours, and it shows graphs both for the temperature compensated as well for the non compensated wall thickness measurements. Note how daily temperature variations affect the measurements with no temperature compensation (thin graph): when the room temperature increases relatively fast from sunrise until midday, the thickness seems to increase. In this period the temperature effect is therefore larger than the effect from corrosion. Temperature compensation removes this effect (thick graph). The corrosion rate is in this experiment estimated to 1.715 mm/year ± 0.0015 mm/year based on the temperature compensated thickness measurements.
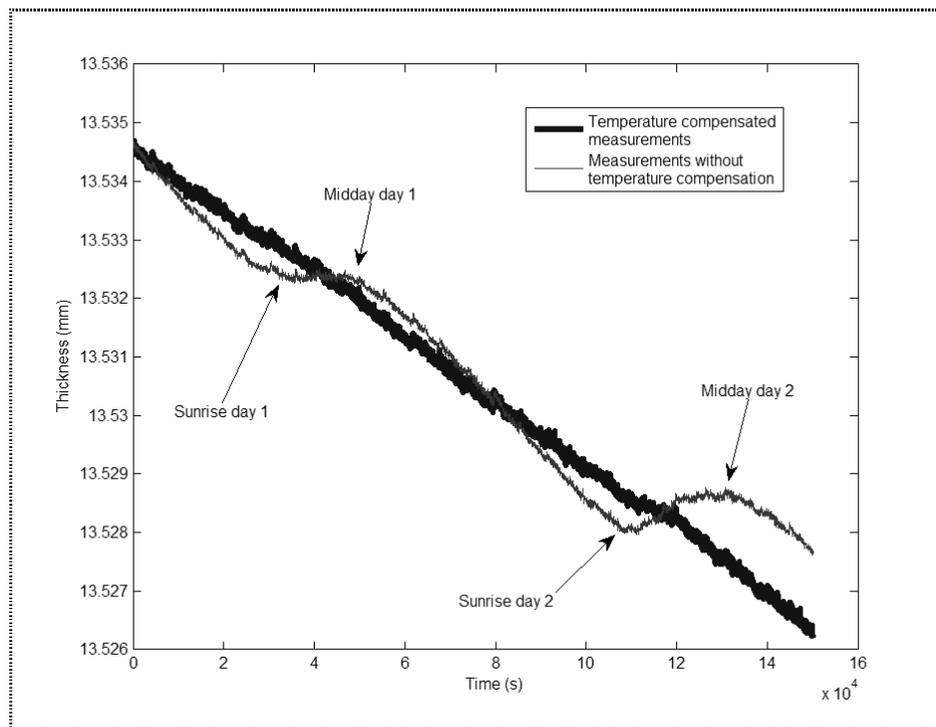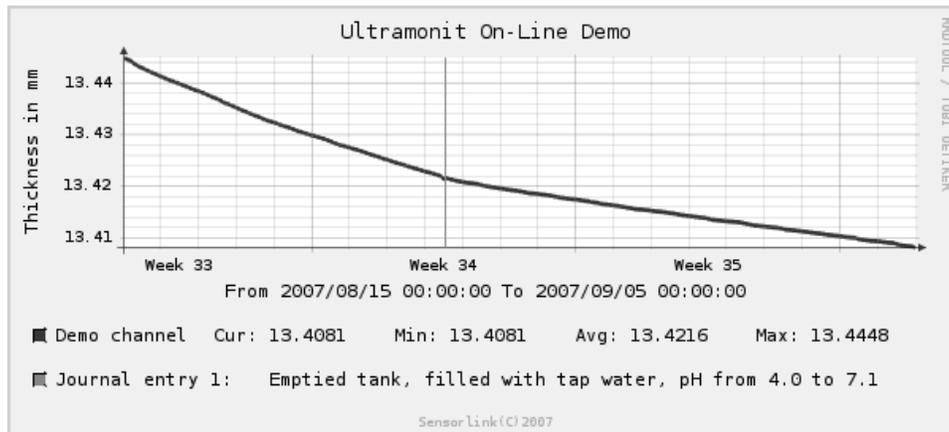
Figure 7 - Illustration of the effect of temperature compensation.

<u>Verification of Measured Wall Thickness with Digital Micrometer</u>

After several months of exposure to a corrosive environment, the specimen has become quite rough with an overall thickness variation of about 1mm. This complicates accurate thickness measurements with a caliper compared to for a planar surface. The absolute thickness measurements performed with the digital micrometer did, however, only show a deviation of less than 0.15mm in compared to the thickness calculated from the ultrasound measurements. This verifies that the specimen has corroded about as much as indicated by the ultrasound measurements.

Proof of concept Web Interface for Real-Time, Temperature Compensated Corrosion Monitoring

Since March 2007 till the date of this writing (October 2007), all data from the corrosion experiment have been stored in a database. The temperature compensated thicknesses are calculated automatically by a data logger and presented real-time on a web interface. It should be noted that the corrosion rates are not estimated real-time. Figure 8 shows a typical graph from the web-interface. It is clear from the figure that a change in the corrosive environment (here the pH is increased from 4.0 to 7.1) results in a relative fast response from the real-time monitoring system. This and similar results clearly show that ultrasound technology may be used with respect to inhibitor control and optimization in addition to traditional wall thickness monitoring.

Ultramonit On-Line Demo

RBOTOOL / TOBI OETIKER

Thickness in mm

13.44

13.43

13.42

13.41

Week 33   Week 34   Week 35

From 2007/08/15 00:00:00 To 2007/09/05 00:00:00

■ Demo channel   Cur: 13.4081   Min: 13.4081   Avg: 13.4216   Max: 13.4448

■ Journal entry 1:   Emptied tank, filled with tap water, pH from 4.0 to 7.1

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Figure 8 - A plot from the proof of concept web interface showing the response to a change in the corrosive environment.

During this period of more than 6 months, long term stability and accuracy has been tested and verified. In this period no degradation has been detected for the sensors or for the hardware.

CONCLUSION AND FURTHER WORK

As the pipeline may be subject to large temperature variations, it is important to control the thermal effects on the ultrasound measurements. Therefore a mathematical model for temperature compensation of the ultrasound thickness measurements is presented. Employing this model reduces the error introduced by thermal effects with more than 94%.

The corrosion experiments illustrate that reliable corrosion rates are found in short time intervals. A 95% confidence interval is used as a measure of how much one can trust the estimated corrosion rate; after 1 hour the confidence interval is ± 0.135 mm/year and after 11 hours it has decreased to ±0.004 mm/year for the medium corrosion rate experiment.

Thickness measurements and temperature compensation has been integrated into a proof of concept web interface for real-time, temperature compensated corrosion monitoring. The preliminary results suggests that ultrasound technology is well suited for real-time corrosion monitoring applications, and that it may be used for inhibitor control and optimization as well.

Some examples of future work are listed below:

- It is desirable to avoid removing an eventual epoxy coating while measuring. Thus one should examine how such coatings will affect the resolution. Other types of coating may be considered as well.
- Since pipelines have curved surfaces, it should be examined how this will affect the resolution.
- An actual field installation should be carried out.

ACKNOWLEDGEMENTS

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